Dynamic Upper Leg Strength and Neuromuscular Function in Children, Adolescents and Adults

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ABSTRACT

This study examined muscle strength, muscle performance, and neuromuscular function during contractions at different velocities across maturation stages and between sexes. Participants included pre-pubertal, late-pubertal and adult males and females. All completed 8 isometric and 8 isokinetic leg extensions at two different velocities. Peak torque (PT), rate of torque development (PrTD), electromechanical-day (EMD), rate of muscle activation (Q_{30}), muscle activation efficiency and coactivation were determined. Sex, maturity, and velocity main effects were found in PT and PrTD, reflecting greater values in men, adults, and isometric contractions respectively. When values were normalized to quadriceps cross-sectional area (qCSA), there was still an increase with maturity. EMD decreased with maturity. Adults had greater activation efficiency than children. Overall, differences in muscle size and neuromuscular function failed to explain group differences in PT or PrTD. More research is needed to investigate why adults may be affected to a greater extent by increasing movement velocity.

(*Children*, *Strength*, *Isokinetic*, *Isometric*, *Electromyography*)

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LIST OF ABBREVIATIONS

Af: Adult Females

agEMG: Agonist EMG amplitude at peak torque

Am: Adult Males

antEMG: Antagonist EMG amplitude at peak torque

EMD: Electromechanical Delay

EMG: Electromyography

ITT: Interpolated Twitch Technique

LBM: Lean Body Mass

LPf: Late-Pubertal Females

LPm: Late-Pubertal Males

mCSA: Muscle Cross-Sectional Area

MRI: Magnetic Resonance Imaging

MVC: Maximal Voluntary contraction

PBF: Percent body fat

PPf: Pre-Pubertal Females

PPm: Pre-Pubertal Males

PrTD: Peak Rate of Torque Development

PT: Peak Torque

qCSA: Quadriceps Cross-Sectional Area

RTD: Rate of Torque Development

SEC: Series Elastic Component

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CHAPTER 1: INTRODUCTION

1.1 Background and rationale

Children in general have lower muscle strength compared to adults, and this difference can be only partially attributed to differences in body size. Even after normalizing strength to account for differences in body mass, it has been shown that adults are still stronger than children, reflecting that increases in strength and body mass during growth and development are not directly proportional to each other (Bassa, Kotzamanidis, Patikas, & Paraschos, 2001; Blimke, 1989; Camic et al. 2010; Degache, Richard, Edouard, Oullion, & Camels, 2010; Falk, Usselman et al. 2009; Halin, Germain, Bercier, Kapitaniak, & Buttelli, 2003; Kanehisa, Ikegawa, Tsunoda, & Fukunaga, 1994; Kaehisa, Yata, Ikegawa, & Fukunaga, 1995). Several studies further normalized strength per unit of lean body mass, fat-free mass, or muscle cross-sectional area (Bassa et al. 2001; Camic et al. 2010; Falk, Usselman et al. 2009; Housh et al. 1996; Kanehisa et al. 1994; Kanehisa et al. 1995). The findings generally demonstrate that even after such normalization, adults are still significantly stronger than children. There are many possible explanations for this difference, some physiological, such as differences in muscle composition or architecture, and some neuromuscular, such as differences in activation deficit, antagonist coactivation, and activation patterns (Blimke, 1989). The relative contributions of these factors to the differences in strength with growth are still unclear, as are the relative roles of these factors in males and females.

While it is well documented that maximal force is lower in children than in adults, there is limited information on maturity-related changes in the rate of force development (Falk, Brunton et al 2009; Falk, Usselman et al 2009; Grosset, Mora, Lambertz, & Perot, 2005; Asai & Aoki, 1996; Going, Massy, Hoshizaki, & Lohman, 1987). The available evidence suggests that adults are able to develop force faster than children, even after taking muscle size or lean body mass into account. Therefore, adults are not only stronger than children, but they are also able to produce force at a faster rate. As is the case with maximal strength, several physiological and neuromuscular factors may explain the age-related or maturity-related differences in the rate of force development. The relative contributions of these factors to explaining these differences are unclear. Additionally, most studies investigating age-related differences in muscle function focus on children vs. Adults. Very few studies examine muscle function during the pubertal period.

Most of the literature investigating muscle strength and performance differences between children and adults has focused on isometric contractions. While this is a reliable method to assess maximal strength, dynamic contractions may be more revealing as they relate better to everyday movements. Isokinetic strength has been shown to be directly related to athletic performance (Wilson and Murphy 1996). Therefore, isokinetic dynamometry is becoming more commonly used in strength assessment. Both, isometric and isokinetic strength testing have been demonstrated to be reliable in children (De Ste Croix, Deighan, & Armstrong, 2003). Some studies have demonstrated that at both, fast and slow velocities, adults are stronger than children. However, when strength is normalized to body size, the results are contradictory. Falk, Brunton et al. (2009) found no difference in isometric elbow flexion peak torque between pre-pubertal girls and adult women after torque values were normalized to biceps-CSA. On the other hand, Sunnegardh, Bratteby, Nordesjo, and Nordgren (1988), Falk, Usselman et al. (2009), and Grosset et al. (2005), all found significantly lower normalized isometric strength in children while performing maximum handgrip, elbow flexion, and plantar flexion, respectively. Therefore, more research is needed to assess isometric and isokinetic strength and performance between children and adults, and how the differences change with alterations in movement velocity.

The bulk of the literature on age-related differences in strength represents differences between pre-pubertal boys and adult men (De Ste Croix., 2007; Kanehisa et al. 1994). It is fairly well accepted that sex-related differences in isometric strength, whether normalized for body size or not, do not appear until puberty (Blimke, 1989). However, very few studies have compared isokinetic strength and performance between adolescent children and adults, male or female. More importantly, possible age-related changes in maximal strength or explosive strength have rarely been examined in conjunction with changes in neuromuscular function. In order to get a clearer idea as to when children's muscle performance (strength, explosive strength, neuromuscular function) becomes more similar to that of adults, and whether or not it is the same in males and females, studies need to examine both males and females of a wide range of maturity.

Gaining greater insight into the differences in force production between maturity stages while understanding the differences between the sexes could aid in the development of better diagnosis and prognosis of neuromuscular and orthopedic disorders in the pediatric population. In creating normative values in regards to muscle strength and performance, other applications of this information may include enhanced training, evaluating and monitoring of athletic performance in children.

The present study compared isometric and isokinetic muscle strength and rate of torque development, along with neuromuscular measures such as rate of muscle activation

(Q_{30}), electromechanical-delay (EMD), antagonist coactivation, and activation efficiency in pre-pubertal, late-pubertal and adult males and females.

1.2 Purpose and Objectives

The objective of this study was to examine differences in static and dynamic muscle strength, as well as differences in neuromuscular function between children, adolescents and adults. The aim was also to examine whether maturity-related differences in strength and neuromuscular function are affected by different movement velocity. More specifically, the purpose of this study is to compare maximal isometric and isokinetic torque and rate of torque development, along with the pattern of muscle activation during knee extension in pre-pubertal, late-pubertal and adult males and females.

1.3 Hypotheses

It is hypothesised that:

1. Absolute and relative peak torque and rate of torque development will decrease with faster contraction velocities in all groups and be the lowest in pre-pubertal children.
2. Sex-related differences in peak torque and rate of torque development will be apparent in the late-pubertal and adult groups with males producing significantly greater values than females, but not in the pre-pubertal groups.
3. Electromechanical delay (EMD) will be longer in the pre-pubertal groups and similar at all velocities.
4. Q_{30} will be greater in the adults when compared to pre-pubertal children.
5. Muscle activation efficiency will decrease, and co-contraction will increase with movement velocity in all groups. Efficiency will increase, and co-contraction will

decrease with maturity, and sex-differences will be apparent by adulthood reflecting greater efficiency and lower co-contraction in men than in women.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Strength

Strength is often described as the ability of a single, or group of muscles to exert force for the purpose of resisting or moving external loads or propelling objects against gravity (Farpour-Lambert & Blimke, 2008). It is a very important health-related fitness component and can greatly influence athletic performance, while minimizing risk of musculoskeletal injuries (Farpour-Lambert & Blimke, 2008). Understanding muscle strength is also useful in monitoring and evaluating patients with neuromuscular and orthopaedic disorders and has been shown to be of great worth in occupational medicine (Sunnegardh, et al. 1988). Therefore, the information collected from muscle strength testing can benefit a wide variety of disciplines. Muscle strength can be tested under two basic conditions, either static or dynamic (De Ste Croix et al. 2003) and is expressed in absolute values or relative to various anthropometric characteristics in order to account for size differences when comparing individuals. Most research in the past has focused on static strength since it is much easier to measure, mainly of young adult males.

The following sections summarize age- and sex-related differences previously described in the literature. This, review focuses primarily on dynamic strength.

2.1.1 Static Strength

Static strength is measured during an isometric contraction, which is when the muscle is neither shortening nor lengthening during the contraction (Saladin, 2007). Isometric contractions are considered controlled contractions in that no movement occurs. Therefore, the yielded force or torque values are less likely to be affected by extraneous variables such as differences in moment arm length and movement velocity. Most studies have investigated strength characteristics of the flexors or extensors of the knee, elbow, ankle or wrist joints. In order to test isometric strength, a variety of methods and equipment can be used, such as cable tensiometers and isometric dynamometers.

Previous studies found that there is no significant difference in absolute static strength of the wrist, ankle, elbow and knee muscles between prepubescent boys and girls (Blimke, 1989; Kanehisa et al. 1995). On the other hand, among adults, men are significantly stronger than women, even after normalizing for body size (Bell & Jacobs, 1986; Blimke, 1989; Sale & Spriet, 1996). Thus, the divergence in strength between males and females occurs during the pubertal years. From early childhood to the early pubertal years, both boys' and girls' isometric strength increases in a linear fashion at a similar rate (De Ste Croix, 2007). Thereafter, around 13 to 14 years of age, isometric strength in boys accelerates at a much faster rate until the age of 18, while strength in girls begins to plateau (Malina, 1974; Parker, Round, Sacco, & Jones, 1990). During this time, boys gain more strength per cross-sectional-area of muscle (Grosset et al. 2005) compared to girls (Neville, Holder, Baxter-Jones, Round, & Jones, 1998; Falk, Brunton et al. 2009).

Much information can be gathered from isometric strength testing, regarding muscle strength and performance. Nevertheless, it has some shortcomings. Isometric testing entails very controlled contractions with limited degrees of freedom that are not typical of movements completed during activities of daily living. In addition, Murphy and Wilson (1996) suggest that isometric strength is very poorly correlated to athletic performance. Hence, dynamic muscle testing may be more informative in terms of functional muscle strength.

2.1.2 Dynamic Strength

Dynamic strength refers the amount of force a muscle can produce or resist while it is shortening or lengthening (Asmussen, 1973). While much is known regarding static strength in children and adults, information concerning dynamic strength is somewhat limited, especially in children. Dynamic strength may be a better indicator of functional strength for everyday activities and athletic performance. Since dynamic strength can be very difficult and unreliable to measure in real life settings, due to the wide variability in movements (many degrees of freedom) and extraneous factors, more controlled tools have been utilized in order to measure dynamic strength. Currently, isokinetic dynamometry is considered the most valid and commonly used method for dynamic muscle function testing (Wiggen, Wilkinson, Habetz, Chorley, & Watson, 2006). By definition, isokinetic exercise maintains the speed of a movement to a designated velocity in order to provide a velocity-specific measure of absolute strength of a muscle group (Brooks, Fahey, & Baldwin, 2005). If the velocity of the movement is not kept constant, the measured force, work and power are not necessarily reflective of the assumed force, work and power at the assumed velocity, due to the changing of mechanical advantage of the limb lever system (De Ste Croix et al. 2003). Isokinetic dynamometers are capable of applying resistance to match the force being applied to its lever in order to maintain a constant velocity throughout almost the entire movement (Brooks et al. 2005). Much like isometric contractions, isokinetic contractions are not typical of everyday movements. However, isokinetic strength testing can provide insight into muscle function under dynamic conditions.

As prescribed by the force-velocity curve, as movement velocity increases, torque will decrease and vice-versa (Brooks et al. 2005). The change in force with increasing movement velocity in children vs. adults has been the focus of several studies but has yielded inconsistent results. Kanehisa et al. (1994) investigated differences in isokinetic knee extension strength at 60, 180, and 300º/s between children 6 – 9 years of age and young adults. Adult men and women were significantly stronger then the young boys and girls, respectively, in all velocities. The age-related differences remained once ultrasonically measured mCSA was considered, except for the force difference between women and girls during the 60º/s contractions. These findings suggest that adults are stronger per unit of muscle when compared to children. It also appeared that the child-adult difference in strength increased as isokinetic velocity increased. However, no statistical analyses were conducted regarding this trend. Whether the child-adult differences in isokinetic strength are consistent in all contraction velocities remains unclear.

Segar and Thorstensson (2000) investigated isokinetic knee extension strength at 45, 90, and 180º/s in 16, 11 year old children (9 boys, 7 girls), over 5 years. They also reported an increase in absolute strength with increasing age at all velocities. The child-adult difference in strength appeared to have increased as isokinetic velocity increased, yet this aspect was not statistically analyzed as the authors were making comparisons to an adult group involved in a different study. Unlike Kanehisa et al. (1994), once body mass was accounted for, concentric knee extension strength appeared to remain constant with increasing age. However, the small sample size could have affected the power of the analysis to detect significant changes with increasing growth. The fact that only body mass was used to account for size differences and not lean body mass or muscle CSA may have also had an impact on their findings due to changes in body composition with growth. Finally, data was analyzed separately for boys and girls. Therefore, no sex comparison is available. Barrett and Harrison (2002) also examined isokinetic knee extension strength differences in young children (6 years of age) and young adults at nine different isokinetic velocities. They found that once differences in lean thigh CSA were accounted for, functional strength differences between children and adults were eliminated, suggesting that differences in muscle strength between children and adults are primarily a function of muscle size. However, surprisingly, these authors also reported no change in force with increased velocity, which contradicts the available literature in muscle physiology. Therefore, these results appear questionable. One of the limitations to this study was the validity of the lean thigh CSA measure used to normalize their findings since their measurement included bone volume, which could create a bias if proportion of bone in the limbs of adults and children is different. More research is needed to investigate the differential effect of movement velocity on muscle strength in adults and children.

There is a significant increase in isokinetic strength, regardless of velocity, with age in both males and females (Degache et al. 2010; Bassa et al. 2001; Camic et al. 2010). Numerous studies have demonstrated lower torque per muscle size during isokinetic contractions in boys compared with men (Bassa et al. 2001; Camic et al. 2010; Kanehisa et al. 1994), or an increase in size-normalized isokinetic torque with age (Camic et al. 2010). Yet, this observation has not been as obvious in females (Kanehisa et al. 1994), suggesting that in females, strength tends to increase in proportion to growth. Similar to isometric strength, there is no significant difference in isokinetic strength between pre-pubertal boys and girls, yet boys typically show a significant increase in absolute isokinetic strength in a wide range of velocities (60-300º/s) from 7-18 years of age (Kanehisa et al. 1994), while girls begin to plateau around 14 years of age (De Ste Croix et al. 2003). This pattern is apparent even after normalizing for body size and/or muscle cross-sectional area (mCSA), however the exact timing of when these sex-related differences appear is still uncertain. Conflicting literature may be due to the lack of a standard protocol for isokinetic strength testing and the use of different scaling methods to account for size differences. Further research is needed in order to describe the change in dynamic strength capabilities from childhood to adulthood and how strength is affected by increasing movement velocity during different stages of development.

2.1.3 Other Strength-Related Measures

In addition to maximal strength, there are other indicators of muscle function which can be derived from both isometric and isokinetic contractions. One such measure is the rate at which torque is developed during the contraction, or the rate of torque development (RTD). Explosive strength is of vital importance for athletic performance. For example, the rate of force development, rather than one's maximal force may be more instrumental in tasks such as jumping, running, or even lifting. RTD can be calculated from the first derivative of the torque curve and is an indicator of explosive strength qualities of the neuromuscular system.

Research regarding differences in RTD or explosive muscle force between children and adults is limited. Going et al. (1987) measured RTD and time to peak torque during isometric elbow flexion and extension in 8 to 11 year old boys and compared their values to adults' values from the literature. They reported that children had a lower RTD and took longer to reach a given percentage of their peak force. The authors suggested that the age-related differences may be linked to children's lower proportion of muscle mass relative to body mass. The relationship between muscle mass and RTD in children and adults has still not been thoroughly investigated. Asai and Aoki (1996) investigated differences in elbow flexion RTD between young boys and men during both, static and dynamic contractions. Much like Going et al (1987), they found children to have a significantly lower RTD and also a longer time to peak torque than the adults for both types of contractions. They suggest this difference may be due to immature mechanisms of motor unit recruitment and increases in firing rate of motor units with growth. Falk, Brunton et al. (2009) investigated the differences in static elbow flexion RTD between girls and women. They found that females follow the same pattern as males in that the younger girls had much lower RTD, and longer time to peak torque than the women. However, once RTD was normalized to peak torque, the age-related differences were no longer significant, suggesting that the differences in RTD were primarily due to higher peak torques in women. Falk, Ussleman et al. (2009) conducted a similar study in the same lab with a male population and found the RTD differences between boys and men to be significant even after peak torque was taken into consideration. They suggest that children, particularly boys, may not recruit their type II motor units to the same extent as adults. Similar findings were recently reported by Cohen et al. (2010) during knee extension. More research is needed regarding age- and sex-related differences in RTD, the mechanisms behind these differences, and whether the same patterns observed in static contractions are apparent in dynamic contractions.

2.2 Factors affecting muscle function with growth

Age- and sex-related differences in muscle functioning are influenced by many factors that may vary amoung individuals. These factors include body size, muscle fibre-type distribution, agonist and antagonist muscle activation, musculotendinous stiffness (compliance), and biomechanical properties, as well as hormonal levels. These factors are discussed below.

2.2.1 Body Size

As we grow in size, we get stronger. Therefore, when comparing strength of individuals of different sizes, or children of different ages, some strategy to normalize for differences in body size should be utilized. Studies on single muscle fibres have suggested that muscle fibre cross sectional area (CSA) is directly proportional to force production (Brooks et al. 2005). Thus, the recommended approach to correct for differences in body size is to use a measure of muscle CSA. However, this measurement requires expertise and equipment which may be expensive and not readily available. Thus, it is common to normalize strength to body mass since it is generally proportional to muscle CSA (Brooks, Fahey & Baldwin, 2005).

2.2.1.1. Mass and Stature

It is important to account for differences in mass and stature between individuals when testing any population in order to create a “size-free” variable. De Ste Croix, Armstrgon, Welsman, & Sharpe (2002) illustrated that mass and stature are significant explanatory variables of isokinetic leg strength in 10-14 year old children, even more so than age and maturity. Round, Jones, Honour, & Nevill (1999) support the notion that quadriceps strength is proportional to height and weight. While most studies account for body size by normalizing their force/torque values to the individuals’ mass (N/Kg), Neville et al (1998) and Wiggin et al. (2006) suggests that height may be a stronger indicator than body mass in children, possibly because it is not influenced by body composition. However, it should be noted that fat-free mass and muscle size were not considered in the studies above. Indeed, some studies have used a combination of body mass and a measure of length (height and/or limb length) in order to account for differences in muscle length (Camic et al. 2010; De Ste Croix et al. 2002; Kanehisa et al. 1994; Kanehisa et al. 1995; Neville et al. 1998; Sunnegardh et al. 1998; Wiggin et al. 2006). In all but one of these studies (De Ste Croix et al. 2002), age-related differences in strength remained after normalization. These age-related strength differences suggest that factors other than body mass and stature play a role in adults having greater strength. Whole body mass includes fat mass and may not necessarily reflect local muscle cross sectional area (mCSA). Therefore, it is not the optimal method in normalizing strength to body size.

2.2.1.2 Muscle CSA

More recently, mCSA has been used to normalize strength to size differences. Wood, Dixon, Grant, and Armstrong (2008) found no significant differences between children and adults in elbow flexion and extension strength once mCSA was accounted for, suggesting that differences in strength are primarily a result of variation in mCSA. Barrett and Harrison 2002, found similar results for isokinetic knee extension, suggesting that the functional ability per unit of muscle is the same in children and adults. Yet, many studies contradict this notion (Falk, Usselman et al. 2009; Halin et al. 2003; Kanehisa et al. 1994; Kanehisa et al. 1995; Sunnegardh et al. 1998). They demonstrate significantly lower strength in boys compared with men in ankle, elbow and knee flexion and extension after mCSA was accounted for in males. In females, on the other hand, Falk and Brunton et al. (2009), and Kanehisa et al. (1994) found similar strength in girls and woman, when corrected for mCSA.

One possible explanation for the above discrepancy may be related to the different methods used to assess mCSA. The gold standard for measuring CSA is using magnetic resonance imaging (MRI) which is costly and not readily available. Other methods that have been used to measure mCSA include, but are not limited to ultrasound, radiography, anthropometry, and computerized axial tomography. Another methodological problem in the measurement of mCSA is determining the optimal site for measurement within individuals and muscle groups (De Ste Croix, 2007; Farpour-Lambert, & Blimke, 2008). The optimal site for the measurement of mCSA is still unclear in both adult and paediatric populations and therefore, an arbitrary location on the limb is often used, which may partly account for the discrepancy in results (De Ste Croix, 2007). However, in view of the persistence of age-related differences in muscle strength, even after correcting for muscle size using the various methods, it is likely that other factors contribute to these age-related differences.

2.2.2 Muscle Composition

In addition to muscle size, muscle composition (fibre type distribution) may also play a role in the strength differences between children and adults. There are two main muscle fibre types in human muscle: type I, characterized by aerobic, fatigue-resistance slow-twitch fibres, and type II, which are fast twitch fibres adapted for quick and powerful responses (Saladin, 2007). Type II can be subdivided into three different fibre types. Type IIb (sometimes referred to as type IIx) are fast-twitch and fatigable fibres. Type IIa are fibres that have a combination of fast twitch responses with aerobic fatigue resistant metabolism. Type IIx (sometimes referred to as type IIc) fibres are undifferentiated fibres (Saladin, 2007). Type II fibres have a significantly greater force producing capacity and contraction speed compared to type I fibres (Sale & Spriet, 1996). Therefore, a difference in fibre type distribution between children and adults may provide an explanatory factor in the associated strength and RTD differences. Due to ethical constraints in the use of muscle biopsies, few studies have investigated muscle fibre type distribution in healthy children. From the evidence available, it is accepted that hyperplasia of muscle fibres cease shortly after birth. However changes in fibre type distribution may extend much longer. There is some evidence that children may have greater proportions of type I and IIx fibres compared with adults (Lexell, Sjostrom, Nordlund, & Taylor, 1992; Vogler and Bove 1985), yet other studies suggest that fibre type distribution reaches adult proportions between one and three years of age (Bell, MacDougall, Billeter, & Howald, 1980; Elder & Kakulas, 1993). Nevertheless, possible differences in muscle fibre type distribution, while providing a partial explanation, are likely too small to explain the large differences in strength and RTD observed between children and adults.

2.2.3 Agonist Muscle Activation

By a process of elimination, if morphological factors such as body size, mCSA, and muscle composition cannot fully explain the differences in strength and RTD between children and adults, then there is a good chance that neurological factors may provide insight into these differences. Neural activation is often evaluated by the number or proportion of motor units activated and the rate at which they are activated. Based on the disproportionate increase in muscle strength compared with the increase in body size that occurs with growth, Asmussen and Heeboll-Nielsen (1955) was the first to suggest that children's muscle activation during maximal contraction is lower than in adults. Since then, numerous studies demonstrating age-related differences in strength per mCSA, have suggested that adults may recruit a greater proportion of their motor-units during a maximal voluntary contraction compared to children (Camic et al. 2010; De Ste Croix et al. 2003; Falk, Usselman et al. 2009; Halin et al. 2003; Kanehisa et al. 1994; Kanehisa et al. 1995; Westing, Cresswell, &

Thorstensson, 1991; Belanger & McComas, 1989; O'Brien, Reeves, Baltzopoulos, & Jones, 2009; Grosset, Mora, Lambertz, & Perot, 2008).

In 2008, Grosset et al. investigated activation deficit differences during maximal and submaximal isometric plantar flexion between children and adults using interpolated-twitch technique (ITT). ITT is a very common method in measuring activation deficit by evoking an electrically evoked stimulation, or twitch, during a maximal contraction in order to measure the motor units that could not be voluntarily activated during said contraction. They found that children had significantly greater activation deficits than adults and that those activation deficits decreased with age. From these findings, they suggest that children recruit proportionately fewer motor units during a maximal voluntary isometric contraction when compared to adults. Several studies have compared activation deficit between children and adults during isometric contractions using ITT, generally reporting children to have greater activation deficits (Belanger & McComas, 1989; Blimke, 1989; Grosset et al. 2008; Paasuke, Ereline, & Gapeyeva, 2000; O'Brien et al. 2009). This suggests that children activate fewer motor units compared to adults during maximal isometric contractions. There are currently no studies, to the author's knowledge, that have investigated differences in activation deficits between children and adults during dynamic contractions, possibly due to methodological constraints.

The rate of muscle activation has been measured many different ways (Barry et al. 2005; Gottleib, Corcos, & Agarwal, 1989; Del Baslo & Cafarelli, 2006) and has been found to be positively related with rate of force development (Barry et al. 2005; Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Del Baslo et al. 2006; Falk, Ussleman et al. 2009). Very few studies have investigated maturity related differences in rate of muscle activation. In a sample of pre-pubertal boys and young adult males, Falk, Ussleman et al. (2009) examined the differences in rate of muscle activation during maximal isometric elbow flexion and extension. Rate of muscle activation was defined as the area under the linear envelope of the detected EMG signal during the first 30ms after the onset of EMG activity, referred to as Q_{30}. They found that the Q_{30} in boys during elbow flexion was significantly lower than that of adults and moderately correlated with peak rate of torque development. However, maturity-related differences in normalized peak rate of torque development were still significant when Q_{30} was controlled for as a covariate, suggesting that factors other than rate of muscle activation are needed to explain the maturity related differences in rate of torque development. Cohen et al. (2010) also found that men had significantly higher rate of muscle activation compared to children during isometric knee and elbow extension and flexion. However, there was no apparent correlation between Q_{30} values and performance measures, which raises the question regarding the functional significance of the Q_{30}. Much more research is needed to investigate the contribution of agonist muscle activation and rate of activation to age-related strength and performance differences.

2.2.4 Antagonist Coactivation

Whenever force/torque is being measured during muscle strength testing, the resulting value is not only a reflection of the capability of the agonist muscle involved, but also the influence of the antagonist muscle. The values yielded from strength testing are technically the net force of the agonist muscle minus that of the antagonist. It is reasonable to suggest that if there is a significant difference in antagonist coactivation between children and adults, it could be an explanatory factor contributing to age-related differences in strength.

Two studies by Falk et al. (Falk, Brunton et al., 2009; Falk, Usselman et al. 2009) reported no age-related difference in antagonist coactivation during isometric elbow flexion between children and adults, in both females and males, respectively. On the other hand, Grosset et al. (2008), found a significant age-related decline in coactivation during submaximal isometric plantar flexion, but not during maximal isometric plantar flexion, suggesting that coactivation may play a larger role in motor control rather than in maximal strength. More conflicting results were found from O'Brien et al. (2009). They found that adult men have greater coactivation during maximal isometric knee extension when compared to prepubertal boys. However, the authors point out that, as a percentage of maximal strength, there were no differences between boys and men in the force produced by the antagonist and that the differences in coactivation are too minimal to account for the large differences in force.

Limited data are available regarding antagonist coactivation differences during dynamic contractions between children and adults. Kellis and Unnithan (1999) did not find any significant differences in coactivation between children and adults for both knee extension and flexion during slow isokinetic contractions (30º/s). They also found no sex-related differences in coactivation. Bassa, Patikas, and Kotzamanidis (2005) also tested knee extension and flexion (at 45, 90, and 180º/s) and reported no age-related differences in coactivation. However, they found that coactivation significantly increased as isokinetic velocity increased for both age groups.

From the limited data available, it is likely that possible differences in antagonist coactivation are too small to account for the large differences in maximal strength between children and adults. However more research is needed on age-related coactivation differences in dynamic muscle actions.

2.2.5 Biomechanical Properties

A possible difference in biomechanical characteristics between children and adults may explain some of the age-related strength differences. More specifically, if adults have a relatively larger distance between the tendon insertion point on the bone and the axis of rotation of the joint, they will have a longer moment arm. Therefore, greater torque would be produced around the joint for any given force production. Measurement of moment arm length is very difficult *in vivo*. This measurement is usually performed using MRI (Wood, Dixon, Grant, & Armstrong, 2006; Wood, Dixon, Grant, & Armstrong, 2004; De Ste Croix et al. 2002). In a 2006 study, Woods et al. measured moment arm length of the brachialis at five different joint angles (10º, 30º, 50º, 70º and 90º) using MRI and maximal isometric elbow flexion at three different angles (10º, 50º and 90º) in prepubertal children, aged 6-13 years old. They found that at 90º, differences in absolute moment arm length accounted for 19% of the variance in torque and less than 1% of the variance in more extended positions. However, no comparison was made with adults. It has also been suggested that normalizing strength to mCSA*limb length or height may indirectly account for differences in mechanical properties (Farpour-Lambert & Blimke, 2008; De Ste Croix et al. 2003). Kanehisa et al. (1994) utilized this method to normalize isokinetic knee extensor torque and later, in 1995, for dorsiflexion and plantar flexion torque in children and adults. They found that significant age-related differences in strength remained. This suggests that any possible biomechanical advantage due to the moment arm is insufficient to explain the differences in age-related strength.

2.2.6 Musculotendinous Stiffness (Compliance)

The elasticity of the muscle-tendon unit may be an explanatory factor in the age- and sex-related differences in rate of torque development, but not likely in maximal strength. The elastic properties of the tendon greatly influence the transmission of force to the bone and it has been shown that the tendon becomes less compliant with growth (Nakagawa, Hayashi, Yamamoto, & Nagashima, 1996). Kubo, Kanehisa, Kawakami, and Fukanaga, (2001) found that the tendon structures of the vastus lateralis in young boys were significantly more compliant than adolescent and adult males. The elasticity of the tendon may play an important role in protecting younger boys from athletic injuries. Their findings support the hypothesis that childrens' lower RTD may be due to more compliant tendon structures. Lambertz, Mora, Grosset, and Perot (2003) investigated musculotendionous stiffness of the triceps surae in prepubertal children and adults and also found that adults have less compliant tendons.

The compliance of the tendon can also affect the delay between the increase in electrical activity and the onset of measurable tension in the muscle, called the electromechanical delay (EMD; Cavanagh & Komi, 1979). Cavanagh and Komi (1979) suggested that this delay represents the time it takes to stretch the series elastic component (SEC). It has been shown that children have a significantly longer EMD during isometric contractions (Grosset et al. 2005; Asai & Aoki, 1996; Falk & Ussleman et al. 2009), which would support the notion that they have higher musculotendinous compliance (or lower stiffness). There have been no reports of differences in EMD, or musculotendinous stiffness in children compared to adults during isokinetic contractions.

2.2.7 Hormones

During puberty, a dramatic increase in androgenic hormones, especially testosterone, believed to be the most active stimulator of muscle hypertrophy, is experienced in boys (Blimke, 1989). Sale and Spriet (1996) suggest that serum testosterone is most likely responsible for the increase in muscle size and strength in males from age 14 through to early adulthood. A few studies have now further investigated the role that hormones may play in sex-related differences in strength during adolescence (Round et al. 1999; Ramos, Frontera, Llopart, & Feliciano, 1998). Round et al. 1999 conducted a mixed longitudinal study with boys and girls from the ages of 8 to 17. They found that female quadriceps strength increases proportional to height and weight. However, these same factors could not fully explain the increase of strength in males. The authors found that increases in testosterone were able to fully account for the additional gains in strength of the boys' quadriceps muscle, but not of their biceps brachii.

Many hormones, cortisol for example, are also catabolic in nature and may have actions that oppose the anabolic hormones effects on muscle growth and performance (Blimke, 1989). The roles of these hormones and the balance between anabolic and catabolic hormones on age- and sex-related differences in muscle performance during growth remain unclear (Blimke, 1989).

2.3 Methodological Considerations in Child-Adult Strength Testing

Many considerations must be taken into account when attempting to develop strength testing protocols and when drawing comparisons between children and adults. Children are not just small adults. They are different both physically and mentally and protocols that may be suitable for adults may not be suitable for children. Three of the many methodological obstacles that must be considered when testing children and adults are the differences in compliance and comprehension of instructions, inter-trial consistency, and interpretation of EMG signals from surface electrodes.

The comprehension abilities of children and adults are very different and for this matter it is important that children receive instruction that is clear and concise. Due to children's shorter attention span, it is vital that instructions be repeated throughout the protocol to keep them focused and to ensure that they comprehend the task at hand. Such instructions as "push as fast and as hard as you can" may be interpreted differently by children and adults. Therefore, in order to ensure the desired results, children may require more habituation to the procedure and learning of the protocol. Thus, when comparing children with adults, it may be difficult to standardize the pre-testing protocol.

It has been suggested by Farpour-Lambert and Blimke (2008) that it is much more difficult for children to grasp the concept of applying maximum voluntary effort against a resisting force through their entire range of motion, or in other words, performing maximal isokinetic contractions. While the concept is not necessarily familiar to adults, they are often able to quickly adapt and develop the motor control and coordination to successfully complete the isokinetic contractions. Whether due to the unfamiliarity of the task, or to other reasons, children tend to have greater inter-trial inconsistency (Falk et al. 2012; De Ste

Croix et al. 2003). In order to ensure the optimal representation of the childrens' capabilities, more trials need to be performed, especially for faster isokinetic velocities, where more learning may be required. Two to six repeated trials have been recommended for adults in order to ensure optimal values without leading to fatigue. However, the optimal number of repetitions for children has not yet been determined (De Ste Croix et al. 2003). While it is important that there are a sufficient number of trials to ensure accurate, representative values, there is a risk of causing unnecessary fatigue. Furthermore, a given number of trials may be suitable for children but may cause fatigue in adults. Therefore, methodologically, one must weigh the advantages and disadvantages of an identical protocol for all participants, versus an optimal protocol, albeit different, for each group. A longer habituation or familiarization period for children may eliminate a learning effect and lead to greater consistency. However, this could result in the testing session becoming very tedious and boring for the child and lead to lack of motivation, especially in children with shorter attention spans (Farpour-Lambert & Blimke, 2008). Special strategies must always be taken to ensure the children stay focused on the task at hand and comprehend what is being asked of them.

Lastly, due to ethical constraints concerning the use of indwelling electrodes with children, surface electrodes are most commonly used for EMG comparisons between children and adults. An important issue arises regarding these comparisons as a result of the great differences in body size. If the same electrodes with a similar inter-electrode distance are being used to test both children and adults, then the signal output from the children will be representing a larger proportion of their muscle. There would also be a greater chance of cross-talk. This is an issue when testing all populations. However the size differences among adult participants are often not as drastic as the differences between children and adults. Unless accurate recordings of muscle volume and electrodes with various inter-electrode distances are used to ensure similar proportions of the muscle are represented by the EMG signal, then direct EMG comparisons between children and adults should be interpreted with caution. The protocol and analysis used in the present study were designed with the above limitations in mind.

CHAPTER 3: RESEACRH METHODOLOGY

3.1 Design

This study used a cross-sectional design in order to investigate differences in isometric and isokinetic quadriceps muscle performance and neuromuscular function of males and females of different maturity stages. A total of 115 boys and girls between 8 and 15 years were subdivided into pre- and late-pubertal groups and compared to a total of 29 young adult men and women.

3.2 Sample

The sample will include 6 groups:

a) Prepubertal males (8-11 yrs, Tanner stage 1); n=21
b) Prepubertal females (8-11 yrs, Tanner stage 1); n=35
c) Late pubertal males (12-15 yrs old, Tanner stage 4-5); n=17
d) Late pubertal females (11-15 yrs old, Tanner stage 4-5); n=13
e) Adult males (19 – 25 yrs old); n=14
f) Adult females (19 – 25 yrs old); n=15

3.2.1 Exclusion Criteria

a) Any risk factors and past or present muscular disease.
b) Chronic/frequent use of medications that could affect neuromuscular function consumed during the current or during the preceding year.
c) Muscular or skeletal injury to dominant leg.
d) Involved in any structured form of physical training or sport (8 hrs/week) for more than 1 year

3.3 Procedure

All tests and measurements were performed in a single session at the Applied Physiology Laboratory at Brock University. Upon entering the laboratory, participants were informed of all tests and procedures. Anthropometric measures were taken (See Measurements), along with a measurement of muscle cross-sectional area using ultrasound. Questionnaires regarding any medical concerns, physical activity habits and pubertal stage (Tanner, 1962) were also completed.

Once the questionnaires were filled out, participants performed an extended local warm-up, as described below, in order for them to become familiar with the testing protocol, equipment, instructions and research assistants. The dynamometer was individually adjusted for each participant and all performed maximal knee extension and flexion at isometric (0°/s), 60°/s and 240°/s, in counter-balanced fashion.

3.3.1 Strength Testing Procedure

All strength testing were performed on the Biodex System III isokinetic dynamometer (Biodex, Shirley, NY) on the dominant leg. Dominant leg was determined by which leg the participant would kick a soccer ball with. The participants were seated in the chair with their hip angle at 120º while their knee is in a start position of 90º. The ankle was secured to the adjustable knee attachment lever using Velcro straps. The support pad on the lever was adjusted to three centimetres superior to the most proximal point of the lateral malleolus, and the axis of rotation of the lever was lined up with the lateral epicondyle. Participants were stabilized in the chair using a strap over the waist, and one over each shoulder diagonally across the chest in an X fashion. Range of motion was set to 90° (i.e., to full extension).

Warm-up/habituation consisted of 3 submaximal isometric contractions followed by 2 maximal (MVC) isometric contractions. Participants then performed 4 isokinetic contractions at 60º/sec followed by 4 at 240º/sec or until they could perform all types of contractions consistently. This was performed for both knee extension and knee flexion in the same predetermined order of their actual test.

All participants performed four, three second, quadriceps isometric MVCs (knee extensions) followed by eight isokinetic MVCs at 60 degrees/sec (1.05 rad/sec), eight MVC's at 240 degrees/sec (4.12 rad/sec), and then four more three second isometric MVCs (24 contractions in total). The reason four isometric contractions were performed at the beginning and then again at the end of the protocol were to determine whether the protocol resulted in fatigue. Each participant had a 30 second rest period between each isometric contraction, 20 seconds of rest between each isokinetic contraction, as well as 2 minutes of rest between each set. The order of isokinetic velocities was counterbalanced and predetermined for each participant. Participants also performed isometric and isokinetic hamstring MVCs (knee flexion's) following the same protocol. The order of agonist muscle contractions was also counterbalanced to completely eliminate any ordering effects. A minimum of 15 min rest was provided between flexion and extension assessments. The following Biodex settings were selected: 1 (hard) for cushion setting and the "knee sensitivity setting." The latter setting ensures that the joint doesn't accelerate at speeds that may be damaging to the knee. In order to reduce noise on the recorded torque and position channel, an EMG-analog signal access interface (Biodex) was used. This utility configures the scale factors of the analog signal outputs for torque and is individually adjusted according to the torque values reached in the habituation protocol.

Participants were instructed to “kick out as hard and as fast as possible” from a completely relaxed state. While performing the MVCs, verbal encouragement was provided, along with visual feedback. The verbal encouragement included statements from the research assistants such as: “Pull, pull, pull!” or “Kick, Kick, Kick!” Visual feedback was provided on the screen of the Biodex where the peak torque was graphed in columns for each attempt so that the participant could compare each trial. During each contraction, EMG signals were recorded from the agonist and antagonist muscles. Additional repetitions were added when some contractions are deemed unacceptable due to reasons such as execution errors, large variations in baseline EMG activity and abnormalities in torque or EMG traces.

3.4 Measurements

3.4.1 Body stature & Mass

Height was measured to the nearest 0.1cm using a stadiometer (Ellard Instrumentation Ltd.). Total body mass was measured to the nearest 0.1kg using a digital scale (InBody520, Biospace CO., Ltd). Participants removed their shoes and any excessive clothing that could significantly affect their weight.

3.4.2 Skin Fold Thickness

Skinfold thickness was measured in triplicate using Harpenden calipers (British Indicators, Herts, England) and the median value at each site was used. Skinfold thickness over the triceps and subscapular sites were measured in order to estimate adiposity (percentage of body fat) using age- and maturity-specific equations (Slaughter et al. 1988). Skinfolds thickness of the anterior and posterior thigh was measured, as these measurements are possible confounders in the EMG signal. All measurements were performed by the same investigator in order to eliminate inter-observer variability.

3.4.3 Muscle width (depth)

Muscle width was measured using a real-time B-mode ultrasound (System5, GE Vingmed, Horten, Norway) with 5 MHz linear-array probe. A transverse image of the vastus lateralis, intermedius and medialis, and rectus femoris were obtained at rest. The probe was placed over the belly of the rectus femoris while participants were supine, at 50% of the distance between the greater trochanter and the lateral femoral condyle. Quadriceps muscle width was measured as the distance between the adipose tissue-muscle interface and the muscle–bone interface. Measurements were made in triplicate and the median value was used for analysis. All measurements were performed by one investigator in order to eliminate inter-observer variability. This measure was used for the estimation of quadriceps CSA. Ex. [$qCSA = \pi*(\text{Muscle Depth}/2)^2$]

3.4.4 Maturity Stage

Maturity stage was self-determined using secondary sex characteristics (pubic hair) as described by Tanner (1962; See Appendix C).

3.4.5 Questionnaires

Questionnaires were completed by the participant with the help of the investigator when needed to assess medical history (Appendix D) and leisure-time physical activity. Physical activity level was assessed using a standardized questionnaire (Godin & Shepherd, 1985; Appendix E), as well as by a personal interview.

3.5 Muscle force measurements

3.5.1 Peak torque (PT)

Peak torque of the quadriceps and hamstrings was evaluated during isometric and isokinetic knee extension and knee flexion (refer to section 3.6.2). All torque data gathered from isokinetic contractions were windowed in order to eliminate the deceleration phase or “cushion artefact” caused by the dynamometer during the last 20º of movement. That is, knee extension data were recorded from 90° to 160° of knee extension. Values were recorded from the dynamometer and were represented in absolute values (Nm).

There was a significant (p<.001) strong positive correlation between isometric, slow isokinetic and fast isokinetic peak torque with mCSA (r= 0.758, 0.759 and 0.658 respectively). Therefore, in line with past literature, peak torque was normalized to quadriceps mCSA (Nm/cm^2). No correlation was found between mCSA normalized PT and mCSA which validates the use of mCSA as method for normalizing torque.

3.5.2 Rate of torque development (RTD)

Rate of torque development of the knee flexors and extensors was evaluated during isometric and isokinetic knee extension and flexion (refer to section 3.6.2). It was attained from the first derivative of the torque over time traces. Values were represented in absolute terms (Nm/s).

There was a significant (p<.001) strong positive correlation between isometric, slow isokinetic and fast isokinetic peak rate of torque development with mCSA (r= 0.675, 0.707 and 0.633 respectively). Therefore, peak rate of torque development was normalized to muscle CSA. Indeed, the normalized RTD at isometric and slow isokinetic conditions were no longer related to mCSA. A low negative correlation was observed between normalized RTD and mCSA at the fast isokinetic velocity. Therefore, we feel that the normalization approach (i.e., ratio of RTD/mCSA) is the appropriate approach. This approach is also in line with past literature (Suetta et al. 2004). To keep consistent with past literature, peak rate of torque development will also be normalized to quadriceps mCSA (Nm/s/cm^2).

3.5.3 Attainment of target isokinetic velocity

It was unclear whether all participants, particularly the young children would be able to attain the target velocity, specifically 240°/s, for the isokinetic contraction. Therefore, for each trial, a spatial and temporal criterion was set for attaining target velocity. In order to have attained target velocity, the measured velocity must have reached at least 3°/s below the target velocity (ie. 57°/s & 237°/s), for at least 30ms. Nominal values were assigned, where a value of 0 represents the participant unable to reach the target velocity and a value of 1 represents the participant being able to reach the target velocity.

3.6 Electromyography (EMG)

3.6.1 Electrode placement

EMG signals were recorded from both the agonist and antagonist muscles during all contractions using bipolar surface electrodes (Delsys 2.1, Delsys Inc., Boston, MA). The skin was prepped by shaving the relevant area (if needed), treated with an abrasive gel, and then cleaned with alcohol. Electrodes were placed perpendicular to the direction of muscle fibres on the muscle belly of the biceps femoris and the medial aspect of the vastus lateralis that was palpated and visually determined during a resisted static contraction. Double-sided tape was used to ensure no movement of the electrode once it had been placed on the participant. The reference electrode was placed on the spinous process of a cervical vertebra.

3.6.2 EMG and torque data acquisition

EMG signals were band-passed filtered (20-450 Hz) using the Bagnoli-4 bioamplifier (Delsys Inc., Boston, MA). All position and torque signals from the Biodex were sent to a 16-bit A/D converter (BNC-2110, National Instruments) and sampled at a rate of 1000Hz using a Computer-Based Oscillograph and Data Acquisition System (EMGworks). Recorded data was electronically stored for further analysis.

3.7 EMG and torque Data Reduction and Analysis

EMG and torque data were analyzed using Matlab (The MathWorks, Natick, MA). There was no apparent systematic fatigue between the four isometric contractions at the beginning of the testing protocol and the four isometric contractions at the end of the protocol. Therefore, the isometric contractions were analyzed as a group, similar to the isokinetic contractions. All trials for each movement and velocity were analyzed and ranked according to their peak torque and peak rate of torque development. Both variables were expressed as a percentage of the maximal value in the set. For each trial, the product of the percentage value of PT and RTD comprised the composite score for that trial. The three trials with the highest composite score and peak torque and peak rate of torque development above 80% of their maximum value were selected for further analysis. Averages of all dependent values of the three trials were calculated and used for further analysis.

The variables calculated from the torque and EMG traces are as follows:

a) Peak torque (PT) – maximal value of the torque between the detection of the initiation and termination of the contraction. A measure of the percentage of isometric PT attained during 60°/s and percentage of isometric PT attained during 240°/s isokinetic contractions will also be calculated.

b) Peak rate of torque development (PrTD) – calculated from the first derivative of the torque over time trace. A measure of the percentage of isometric PrTD attained during 60°/s and percentage of isometric PrTD attained during 240°/s isokinetic contractions will also be calculated.

c) Agonist and antagonist amplitude at peak torque (agEMG and antEMG, respectively) –calculated from the linear detected envelope. The value represents the average amplitude from 125ms before to 125ms after the occurrence of peak torque. A measure of the percentage of isometric agonist amplitude at peak torque attained during 60°/s and percentage of isometric agonist amplitude at peak torque attained during 240°/s isokinetic contractions will also be calculated.

d) Electromechanical-Delay (EMD) – Duration (ms) of the delay between the onset of muscle activity and onset of force production. Onset of muscle activity was defined when the EMG signal was two standard deviations greater than the average amplitude of the first 500ms of baseline activity for a consecutive duration of 100ms.

e) Q_{30} –calculated from the area under the linear envelope of the detected EMG signal during the first 30ms after the onset of EMG activity. Onset of EMG activity was defined when the signal was two standard deviations greater than the first 500ms of baseline activity for a consecutive duration of 100ms.

f) Efficiency – The ratio of the agonist EMG activity around peak torque (agEMG) minus the antagonist EMG activity around peak torque (antEMG) divided by the agonist EMG activity around peak torque plus the antagonist EMG activity around peak torque. This ratio will enable within- and between-subject comparisons minimizing any bias caused by extraneous factors affecting EMG amplitudes.

E.g., Efficiency = (agEMG-antEMG)/(agEMG+antEMG)

A measure of the percentage of isometric efficiency attained during 60°/s and percentage of isometric efficiency attained during 240°/s isokinetic contractions will also be calculated.

g) Coactivation – Several different methods for calculating coactivation have been used in previous studies. For the purpose of this study we have used the ratio of antagonist EMG activity around peak torque to the agonist EMG activity around peak torque, as suggested by (Lambertz et al. 2003). However, since the antagonist EMG signal is not normalized (for peak EMG amplitude), extraneous factors affecting EMG amplitude (e.g., muscle temperature, skinfold thickness) may still affect the coactivation value. Therefore, between-subject differences are to be interpreted with caution. A measure of the percentage of isometric coactivation attained during 60°/s and percentage of isometric coactivation attained during 240°/s isokinetic contractions will also be calculated.

3.8 Statistical Analysis

Statistical analyses were performed using Statistica version 8 (StatSoft., Tulsa OK) and SPSS version19 (SPSS Inc., Chicago, IL). The data for all groups are presented as mean (M) ± 1 standard deviation (SD). An average value of the best three contractions for each action and participant was included in the statistical analyses. Group differences in muscle performance and neuromuscular function were assessed using a mixed-model ANOVA with 2 between-subject factors (sex and maturity) and one within-subjects factor (movement velocity). Group differences in the measure of muscle performance and neuromuscular function of isokinetic contractions compared to isometric contractions were assessed using a 2 way ANOVA with sex and maturity as the between-subject factors. *Post hoc* comparisons (e.g., Tukey's HSD for unqual n's [stoline adjustment]) were used when a significant main effect or interaction involving more than two means was identified. Pearson correlation coefficients were calculated between outcome variables (e.g., peak torque) and potential confounding factors (e.g., physical activity). When a correlation was observed, confounding variables were entered in an ANCOVA. A chi-squared test was used to examine the effect of sex and maturity on attainment of target isokinetic velocity. The acceptable level of significance was set at $p < 0.05$.

CHAPTER 4: RESULTS

All 56 pre-pubertal children were classified as being in sexual maturity stage I and all 30 adolescents in sexual maturity stage IV or V (Tanner, 1962). The physical characteristics are displayed in a Table 4.1. The men were significantly older, heavier, taller, and had greater lean body mass and quadriceps muscle CSA compared to the pre-pubertal boys, while LPm were significantly larger than PPm and significantly smaller than Am. There was no significant difference in body fat percentage between the male maturity groups. The PPf were significantly younger, shorter, lighter, had less lean body mass, and smaller quadriceps muscle CSA compared to both LPf and Af. While the LPf and Af were similar in mass, height, percent body fat, and lean body mass, Af were significantly older and had significantly greater quadriceps CSA. Sex-related differences were apparent in adults for all anthropometric data, men being significantly heavier, taller, having a lower body fat percentage, greater lean body mass and quadriceps CSA. The only anthropometric sex difference in the late-pubertal groups was that the males had significantly lower body fat percentage, and in pre-pubertal groups females had greater quadriceps CSA. Physical activity levels were similar between all groups with the exception of LPf being significantly less active than the Af group.

Table 4.1: Maturity status, physical characteristics and activity scores of study sample (values are presented as M ± SD.

	Males (n=52)			Females (n=61)		
	PPM (n=21)	LPM (n=17)	AM (n=14)	PPF (n=35)	LPF (n= 13)	AF (n=15)
Age (yrs)	9.9 ± 1.3[a,b]	13.6 ± 1.5[a]	21.8 ± 1.7	9.8 ± 1.1[a,b]	13.5 ± 1.8[a]	21.4 ± 2.1
Height (cm)	140.3 ± 8.8[a,b]	165.3 ± 9.4[a]	182.0 ± 6.6[c]	139.1 ± 8.2[a,b]	162.0 ± 9.0	166.7 ± 6.9[c]
Weight (kg)	36.0 ± 6.6[a,b]	57.5 ± 16.2[a]	86.1 ± 11.1[c]	35.8 ± 8.4[a,b]	57.9 ± 9.5	63.0 ± 7.3[c]
PBF (%)	16.6 ± 7.5[c]	15.7 ± 7.4[c]	19.3 ± 3.3[c]	18.6 ± 3.3[c]	22.1 ± 3.2[c]	22.7 ± 2.1[c]
LBM (kg)	29.1 ± 4.5[a,b]	46.1 ± 9.6[a]	69.5 ± 8.3[c]	27.8 ± 5.2[a,b]	42.5 ± 5.7[a]	48.4 ± 4.3[c]
qCSA (cm^2)	6.89 ± 1.5[a,b,c]	9.90 ± 4.2[a]	16.91 ± 4.4[c]	8.51 ± 2.3[a,c]	10.12 ± 2.7[a]	13.20 ± 3.7[c]
Physical Activity Score#	67.9 ± 24.2	59.6 ± 33.5	63.2 ± 26.1	57.9 ± 28.6	41.8 ± 20.4[a]	67.3 ± 28.4

PPM = Pre-pubertal Males, LPM = Late-Pubertal Males, AM = Adult Males, PPF = Pre-Pubertal Females, LPF = Late-Pubertal Females, AF = Adult Females. Values are presented as M ± SD. [a] = significantly different than sex matched adult group, [b] = significantly different than sex-matched late-pubertal group, and [c] = significantly different than maturity matched-matched female group. # - determined using the Godin-Shephard Leisure Time Physical Activity Questionnaire (Godin & Shepherd, 1985).

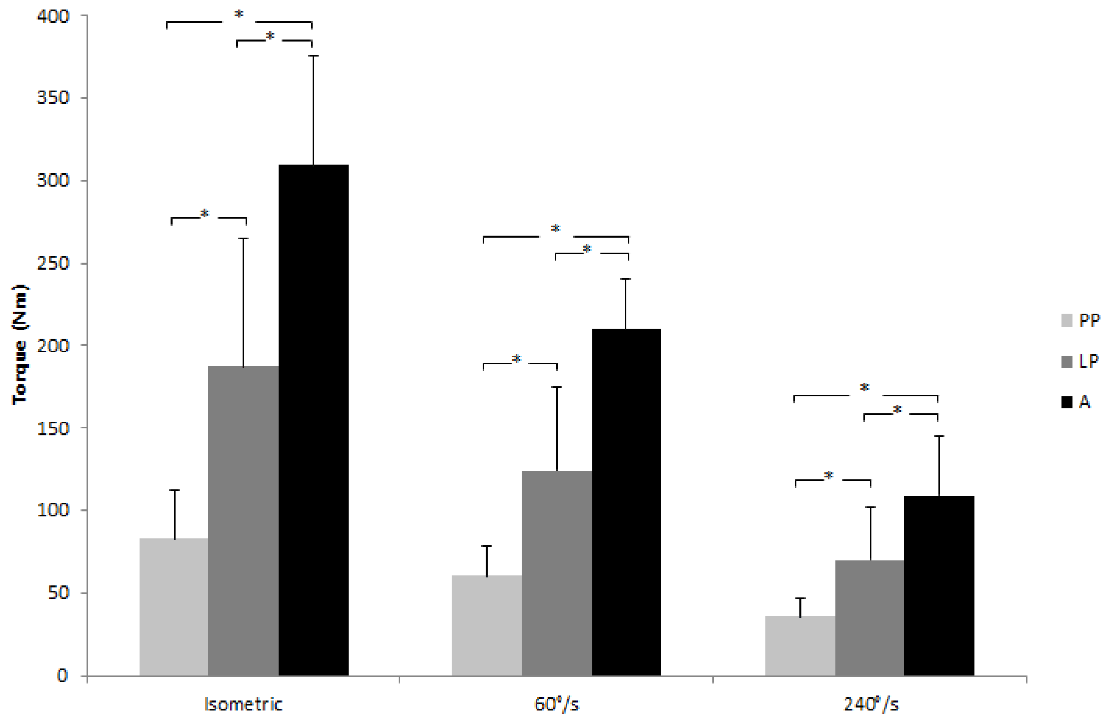
4.1 Absolute Peak Torque

Figure 4.1 describes the males' (top) and females' (bottom) absolute PT in the three velocities of contraction. Figure 4.2 describes the males' and females' PT at 60°/s and PT at 240º/s, relative to the isometric PT. Only maturity-related pairwise differences within each velocity are indicated within the figure. All significant effects are listed in the Figure's legend and explained below.

As expected, PT was significantly lower with increasing velocity of the movement, $F(2,218) = 706.9$, $p<0.05$). There was a significant main effect of Sex, $F(1,109) = 39.1$, $p<0.05$, reflecting the fact that males were stronger than females. There was also a main effect of Maturity, $F(2,109) = 140.9$, $p<0.05$, reflecting that PT increased with each maturity group. The two-way interactions were also all significant (Sex by Maturity, $F(2,109) = 24.5$, $p<0.05$; Sex by Velocity, $F(2,218) = 18.0$, $p<0.05$; Maturity by Velocity, $F(4,218) = 81.5$, $p<0.05$). However, those interactions were superseded by a significant Sex by Maturity by Velocity interaction, $F(4,218) = 7.7$, $p<0.05$. In the isometric contractions, PT significantly increased with maturity in both sexes. The increase in peak PT with maturity was apparent in the isokinetic contractions, but only in the males. In females, PT in the 60°/s condition was similar in LP and adults and in the 240 °/s contractions, PT did not increase with maturity.

As previously mentioned, peak torques for all groups were significantly affected by an increase in movement velocity. When examining the proportional drop in peak torque at 60°/s as a percentage of isometric PT, a maturity effect was found, $F(2,109) = 3.7$, $p<0.05$, reflecting that the LP and adult groups experienced a significantly greater decrease in peak torque compared to the pre-pubertal children. This pattern was similar when examining the proportional drop in PT at 240°/s ($F(2,109)= 12.6$, $p<.05$; Figure 4.2). No sex-effects or interactions were found when examining the proportional drop in PT.

A - Males



B - Females

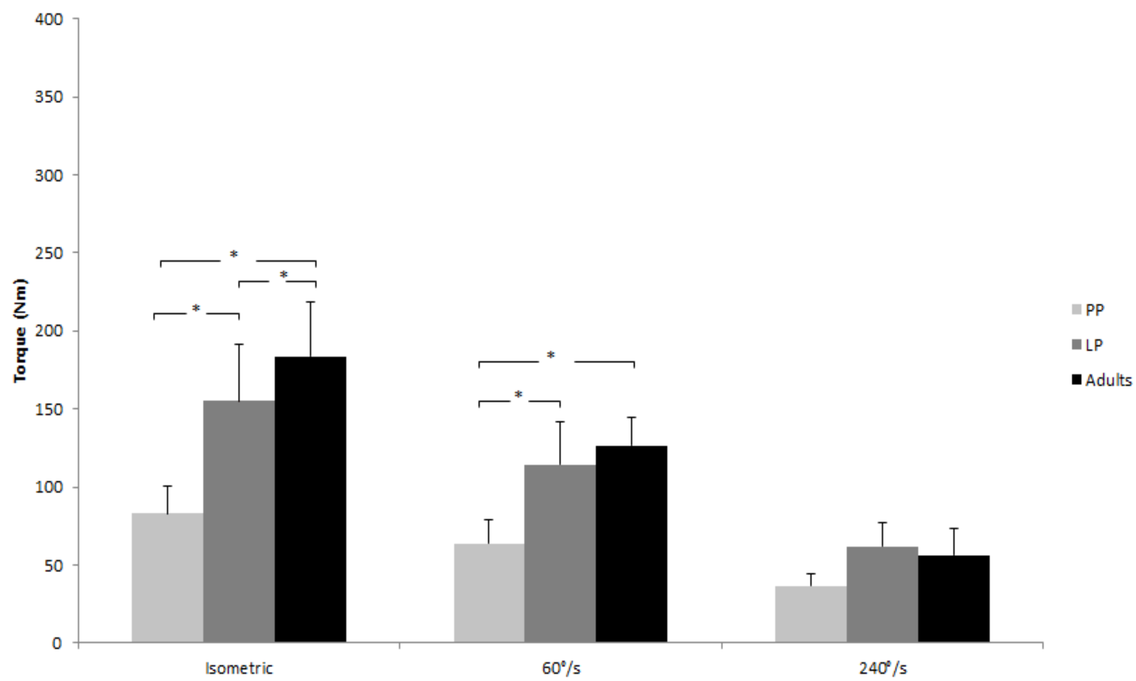
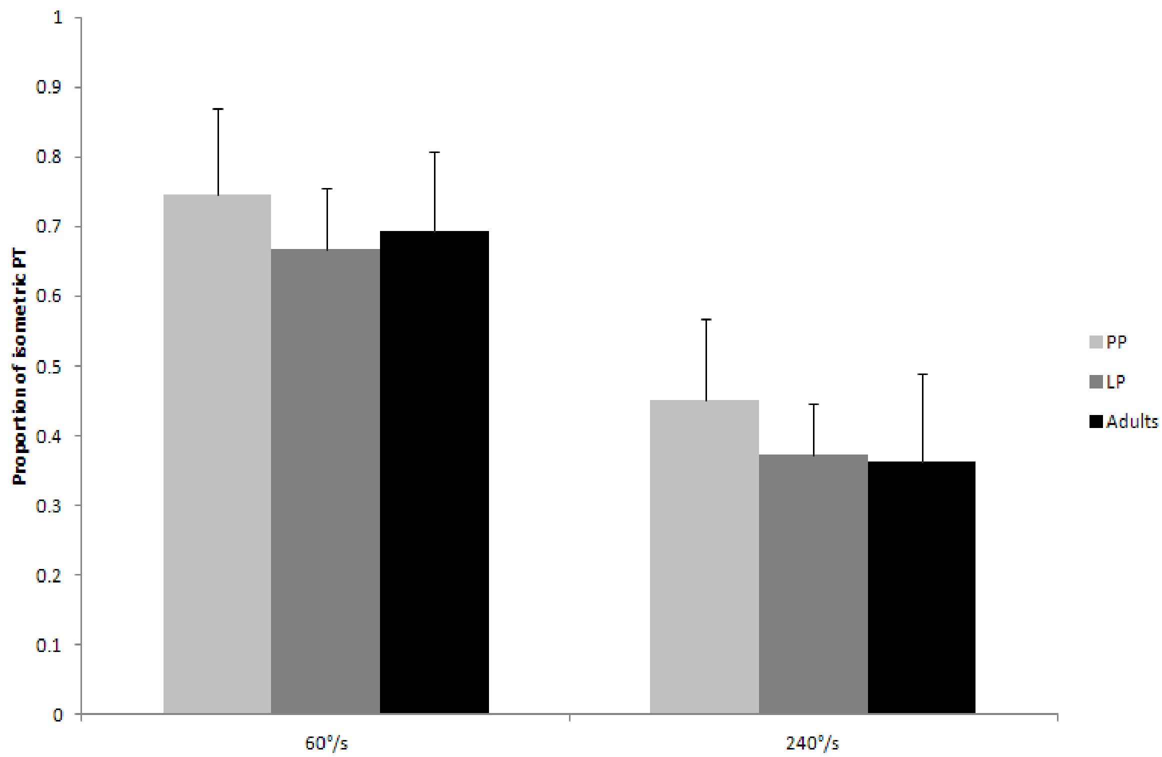


Figure 4.1:A - Knee extension peak torque of pre-pubertal, late-pubertal, and adult males. B – Knee extension peak torque of pre-pubertal, late-pubertal, and adult females. Significant main effects of sex, maturity, and velocity (p<.0001). Significant sex*maturity*velocity interaction (p<.0001).

A - Males



B - Females

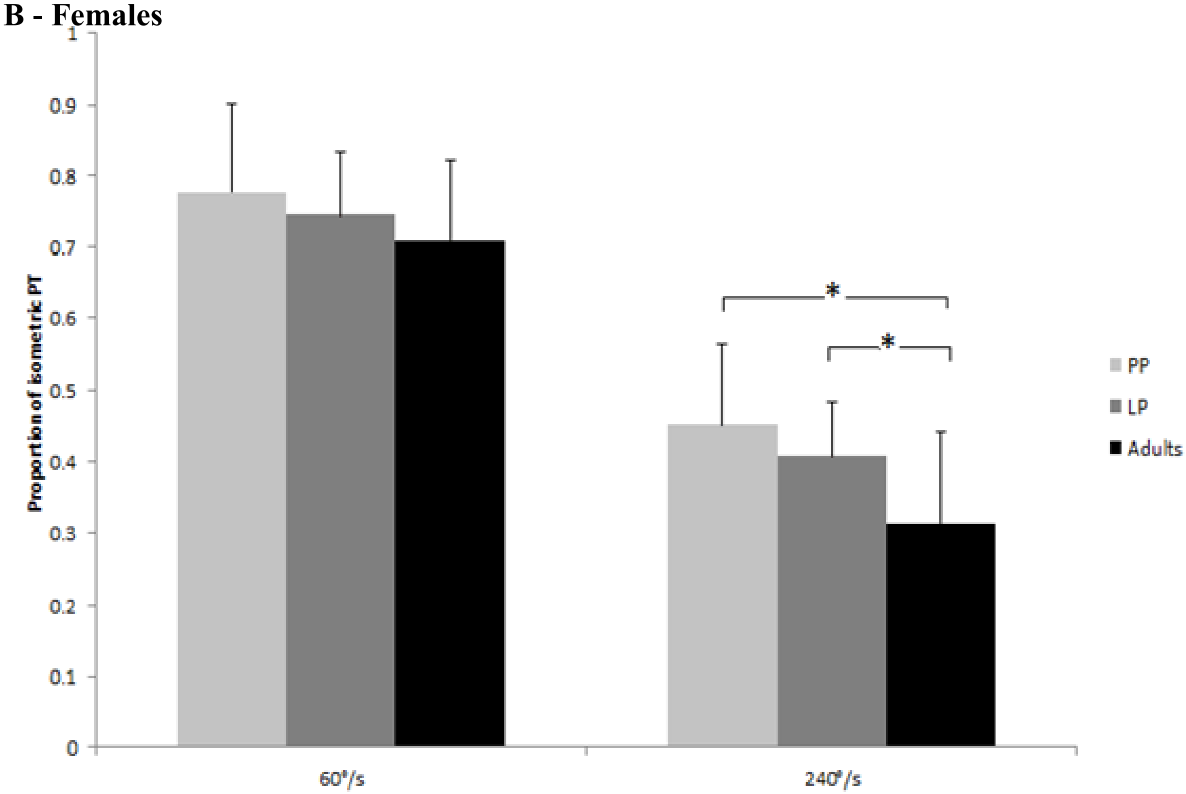


Figure 4.2:A – Proportion of isometric PT attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult males. B – Proportion of isometric PT attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult females. Significant main effects of maturity ($p<.05$ and $p<.001$ for 60 and 240°/s, respectively).

4.2 Normalized Peak Torque

Figure 4.3A and B describes the normalized peak torque for males and female in the three velocities of contraction. Only maturity-related pairwise differences within each velocity are indicated within the figure. All significant statistically effects are listed in the figure's legend and explained below.

When PT was normalized to quadriceps CSA PT two significant main effects were found, Velocity of the movement ($F(2,218)= 765.4$, $p<0.05$), and Sex ($F(1,109)= 15.8$, $p<0.05$), along with a Velocity by Sex interaction ($F(2,218)= 8.1$, $p<0.05$). The interaction reflected a decrease in normalized PT with increasing velocity of movement, and that males were stronger than females at all movement velocities. There was also a significant main effect of Maturity, $F(2,109)= 29.9$, $p<0.05$, reflecting that normalized PT increased with maturity. However, the difference between late-pubertal children and adults was no longer statistically significant. A Maturity-by-Velocity interaction was also found, $F(4,218)= 27.4$, $p<0.05$. Adults and late pubertal children's peak torque were significantly greater than that of the pre-pubertal children for the isometric and isokinetic 60°/s contractions. However, the difference between adults and pre-pubertal children was non-significant for the isokinetic 240°/s contraction velocity.

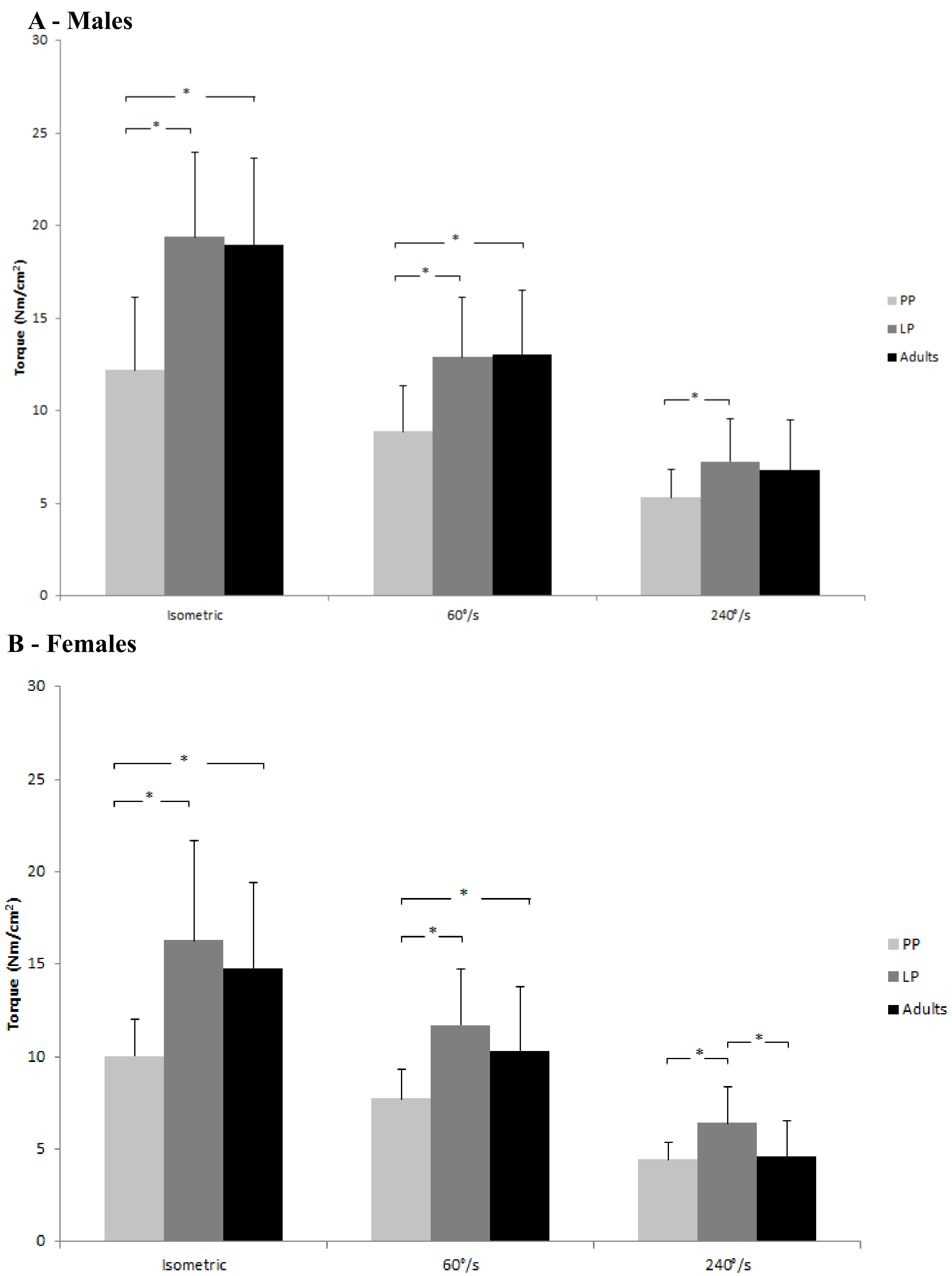


Figure 4.3:A - Knee extension peak torque normalized by quadriceps cross-sectional area of pre-pubertal, late-pubertal, and adult males. B – Knee extension peak torque normalized by quadriceps cross-sectional area of pre-pubertal, late-pubertal, and adult females. Significant main effects of sex, maturity, and velocity ($p<.0001$). Significant sex *velocity and maturity*velocity interaction ($p<.0005$).

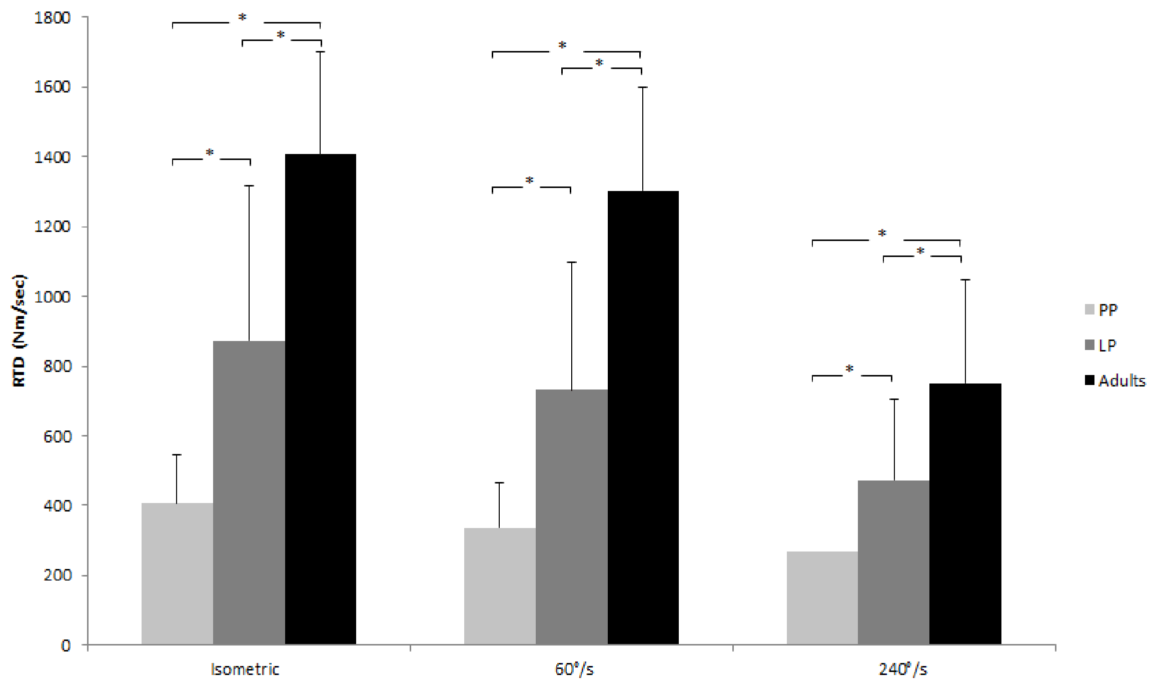
4.3 Peak Rate of Torque Development

Figure 4.4A and B describes the absolute peak rate of torque development for males and females in the three velocities of contraction. Figure 4.5A and B describes the males' and females' proportional decrease in PrTD as a ratio of PrTD at 60°/s and PrTD at 240º/s with respect to the isometric PrTD. Only maturity-related pairwise differences within each velocity are indicated within the figure. All significant effects and interactions are listed in the figure's legend and explained below.

Peak rate of torque development (PrTD) was significantly lower with increasing velocity of the contraction, $F(2,218)= 297.8$, $p<0.05$. There was a significant main effect of Sex, $F(1,109)= 32.9$, $p<0.05$, reflecting the fact that male PrTD was higher than for females. There was a significant main effect of Maturity, $F(2,109)= 78.4$, $p<0.05$, reflecting that rate of torque development increased with each stage of maturity. The three two-way interactions were all significant (Sex by Maturity, $F(2,109)= 20.9$, $p<0.05$; Sex by Velocity, $F(2,218)= 9.1$, $p<0.05$; Maturity by Velocity, $F(4,218)= 46.6$, $p<0.05$). However, there was also a significant Sex-by-Maturity-by-Velocity interaction, $F(4,218)= 4.0$, $p<0.05$. In the males, PrTD significantly increased with maturity for all contraction velocities. For females, PrTD plateaued after late-puberty for both isometric and isokinetic 60°/s contractions and adult females no longer had greater PrTD compared to pre-pubertal females for 240°/s contractions. Within each Sex by Maturity group, PrTD was greater during isometric compared to isokinetic 60°/s contractions, with the exception of the LPm group. PrTD for isokinetic 60°/s was greater than PrTD in the 240°/s movements for all groups, excluding both pre-pubertal groups. PrTD was greater for isometric compared to isokinetic 240°/s contractions in all Sex by Maturity groups.

A significant main effect of Maturity, $F(2,109) = 18.0$, $p < 0.05$, was found regarding the proportional decrease in PrTD as movement velocity increased from static to 240°/s (Figure 4.5A and B). This was reflected by a greater proportional decrease in adults and late-pubertal children compared to the pre-pubertal children ($p < .001$).

A - Males



B - Females

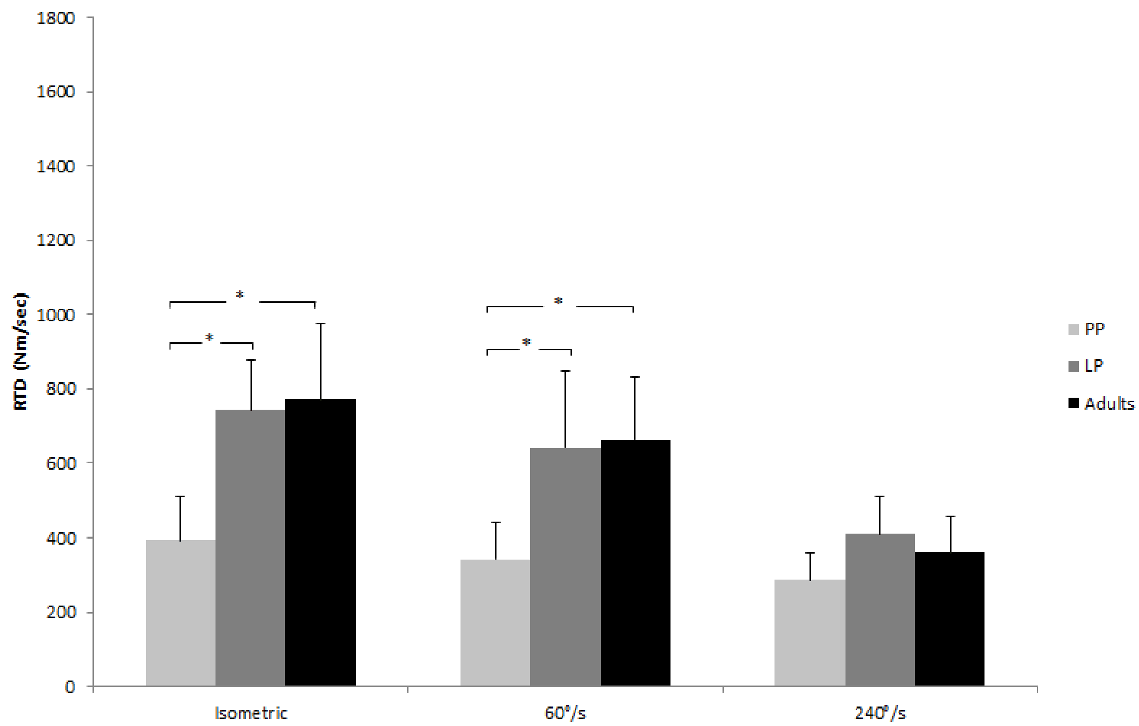
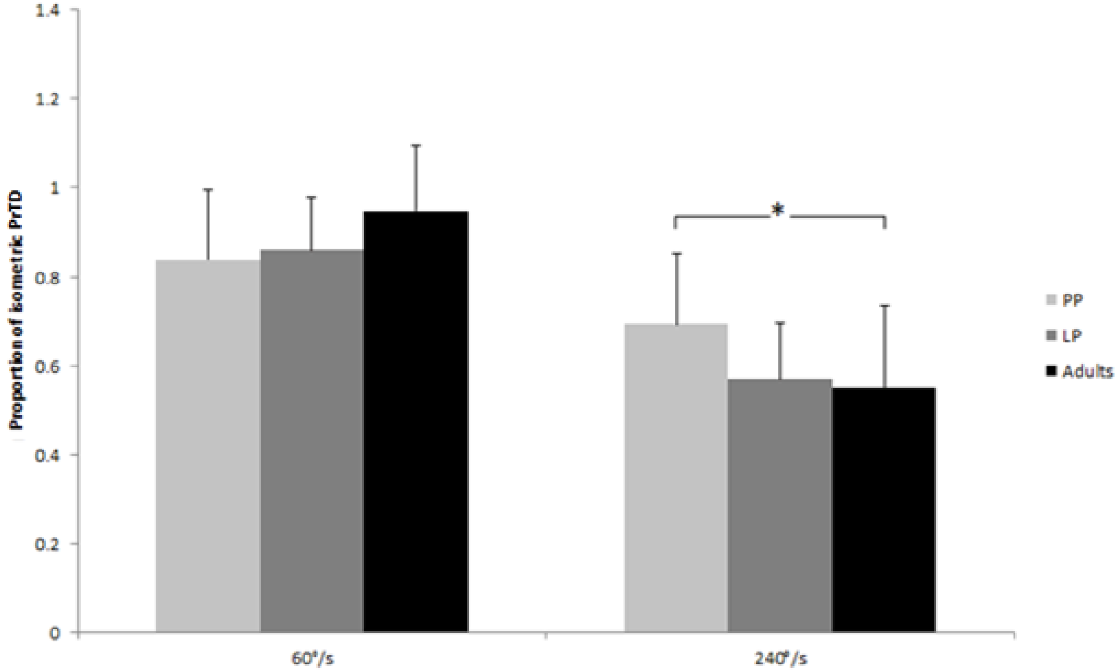


Figure 4.4:A - Knee extension peak rate torque of development in pre-pubertal, late-pubertal, and adult males. B – Knee extension peak rate of torque development in pre-pubertal, late-pubertal, and adult females. Significant main effects of sex, maturity, and velocity (p<.0001). Significant sex*maturity*velocity interaction (p<.005).

A - Males



A - Females

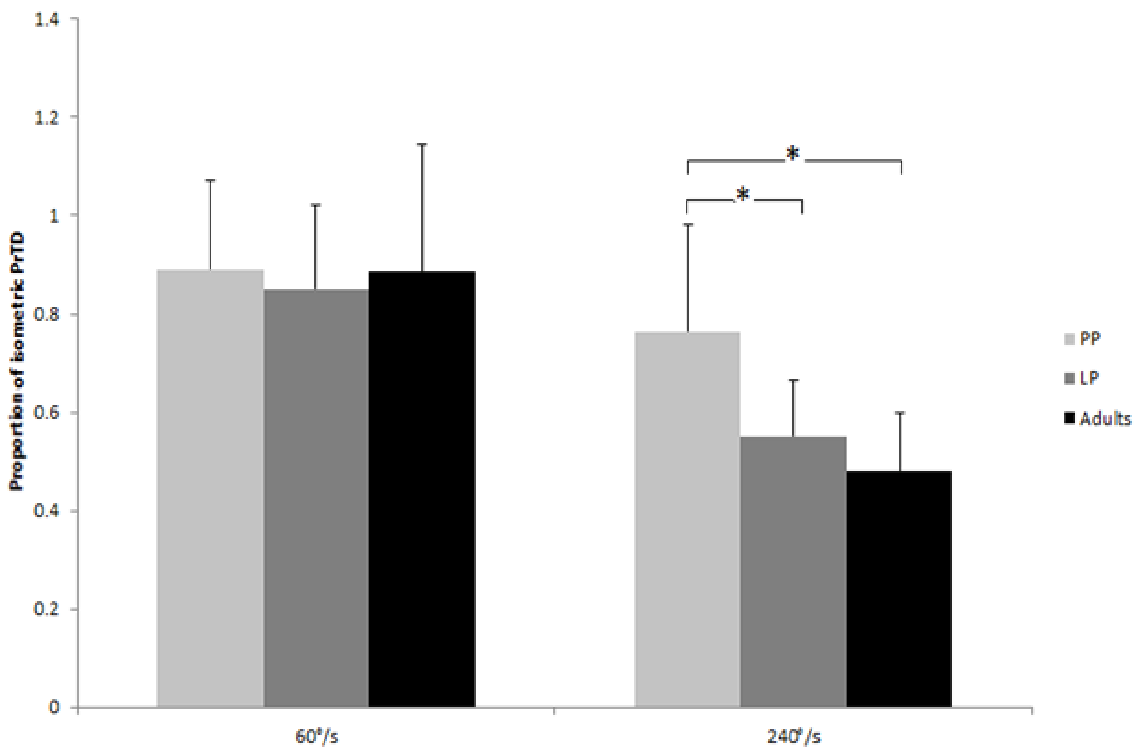


Figure 4.5:A - Proportion of isometric PrTD attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult males. B – Proportion of isometric PrTD attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult females. Significant main effects of maturity for 240°/s contractions (p<.001).

4.4 Normalized Rate of Torque Development

Figure 4.6A and B describes the normalized peak rate of torque development for the males and females in the three velocities of contraction. Only maturity-related pairwise differences within each velocity are indicated within the figure. All significant effects and interactions are listed in the figure's legend and explained below.

When PrTD was normalized to quadriceps CSA, there was a main effect of Velocity, $F(2,218) = 274.2$, $p<0.05$, a main effect of Sex, $F(1,109) = 16.9$, $p<0.05$, as well as a Sex by Velocity interaction $F(2,218) = 3.8$, $p<0.05$. The Sex by Velocity interaction reflected greater normalized PrTD in males compared to females at all contraction velocities and that normalized PrTD decreased with increasing movement velocity in both sexes. A main effect of Maturity was also found, $F(2,109) = 15.5$, $p<0.05$. Overall, the late-pubertal children and adults had significantly higher values compared to pre-pubertal children. Importantly, a significant Maturity-by-Velocity interaction was apparent, $F(4,218) = 21.6$, $p<0.05$. In the isometric contractions, late-pubescent's had greater PrTD compared with pre-pubertal children. In the slow isokinetic velocity (60°/s), adults and late-pubertal children had a similar PrTD, greater than pre-pubertal children. In the fast isokinetic velocity (240°/s), late-pubertal children had greater PrTD than the adults and pre-pubertal children, and there was no significant difference between the adults and pre-pubertal children.

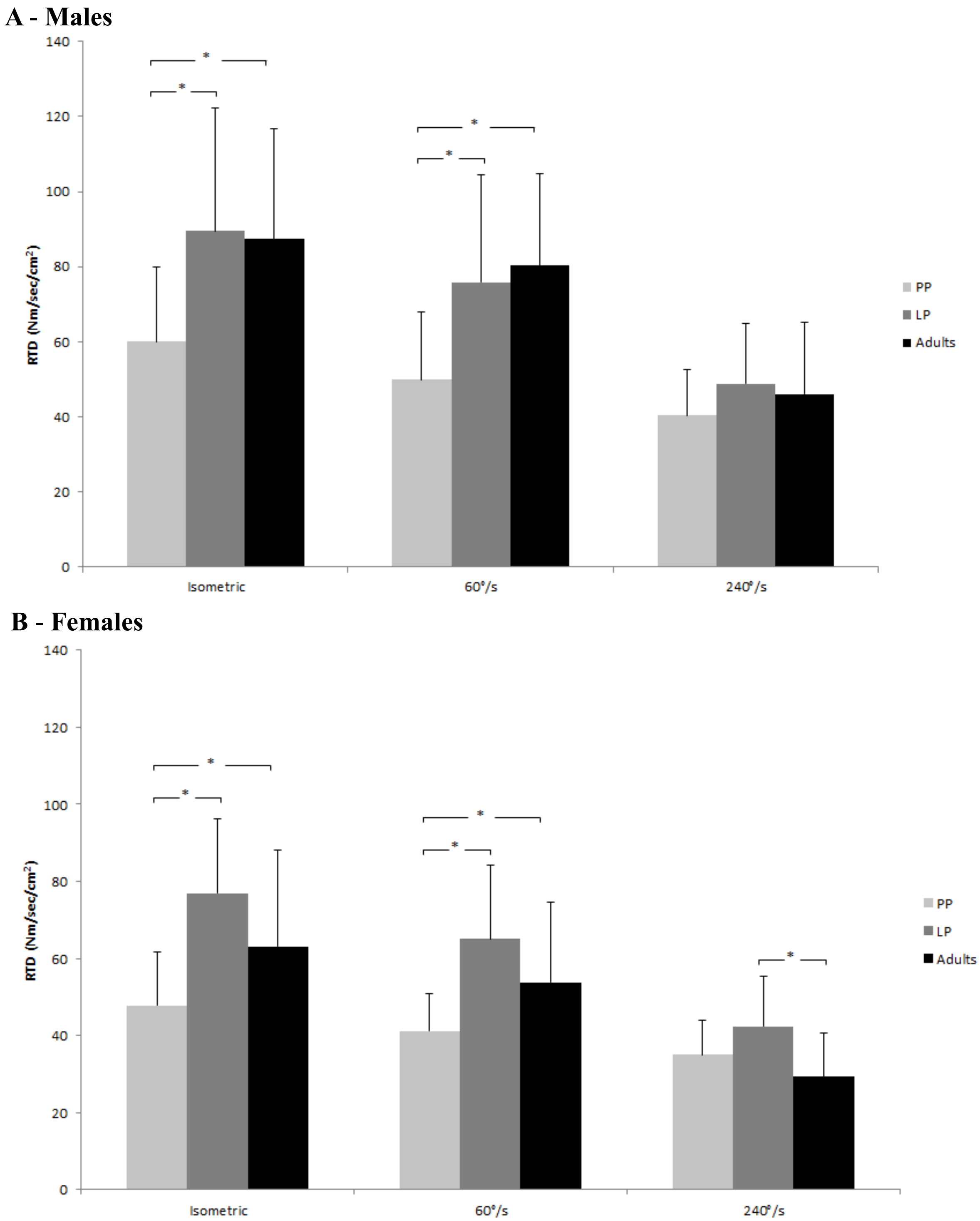


Figure 4.6:A - Knee extension peak rate torque of development normalized by quadriceps cross-sectional area in pre-pubertal, late-pubertal, and adult males. B – Knee extension peak rate of torque development in pre-pubertal, late-pubertal, and adult females. Significant main effects of sex, maturity, and velocity (p<.0001). Significant sex *velocity and maturity*velocity interaction (p<.005).

4.5 Agonist Muscle Activity

It should be noted that, for muscle activity, between-group comparisons are inappropriate because of the many factors that can affect EMG amplitude in individuals (e.g. skin temperature, subcutaneous fat). Therefore, for the purpose of this study, only the within group comparisons are of interest. Additionally, the pattern of response (e.g., increase in EMG amplitude with increasing velocity), is of interest. Therefore, Tables 4.2 and 4.3 provides the agonist and antagonist muscle activity, respectively, for all groups at all velocities. However, only the relevant comparisons are discussed below.

A significant main effect of Velocity was apparent for agonist muscle activity, $F(2,218)= 61.5$, $p<0.05$, where the average amplitude of agonist muscle activity was the greatest for isometric contractions compared to both isokinetic velocities. Amplitudes for the isokinetic 240°/s contractions were significantly greater than the slower 60°/s contractions. A significant Maturity by Velocity interaction was also apparent $F(4,218)= 4.3$, $p<0.05$. Late-pubertal children had significantly different amplitudes for all three contraction velocities, isometric being the greatest, followed by fast isokinetic then slow isokinetic. In adults, agonist muscle activity was greater in isometric compared with the isokinetic contractions; however no difference was found between the two isokinetic contractions. In pre-pubertal children, no significant differences were observed between velocities.

Figure 4.7A and B describes the males' and females' proportional decrease in agEMG activity as a ratio of agEMG activity at 60°/s and agEMG activity at 240º/s, to the isometric agEMG activity. Only maturity-related pairwise differences within each velocity are indicated within the figure. All significant statistically effects are listed in the figure's legend and explained below.

A significant main effect of Maturity, $F(2,109)= 8.9$, $p<0.05$, was found regarding differences in proportional drop in agonist EMG activity as movement velocity was increased from static to 60°/s and from static to 240°/s, $F(2,109)=6.0$, $p<0.05$ (Figure 4.7A and B). Post hoc analysis revealed that pre-pubertal children maintained a greater proportion of their isometric agonist activity compared to both late-pubertal children and adults during the 60°/s contractions, and only the adults in the 240°/s contractions. A significant sex effect was seen only during the 240°/s where the females experienced a greater proportional decrease in agonist activity compared to the males.

A significant sex*maturity interaction was also found reflecting a significantly greater decrease in agonist activity in late-pubertal and adult females compared to pre-pubertal females, where no maturity related differences were found in males.

Table 4.2: Agonist EMG activity. Values are presented as M ± SD.

	Males			Females			Effect
	PPm	LPm	Am	PPf	LPf	Af	Velocity effect (p<.0001), Maturity* Velocity interaction (p<.01)
AgEMGiso (mV)	0.101 ± 0.036	0.129 ± 0.055	0.119 ± 0.046	0.095 ± 0.033	0.100 ± 0.030	0.105 ± 0.041	
AgEMG60 (mV)	0.081 ± 0.028	0.089 ± 0.038	0.087 ± 0.037	0.080 ± 0.028	0.065 ± 0.020	0.070 ± 0.037	
AgEMG240 (mV)	0.095 ± 0.035	0.120 ± 0.057	0.106 ± 0.054	0.096 ± 0.033	0.075 ± 0.033	0.073 ± 0.044	

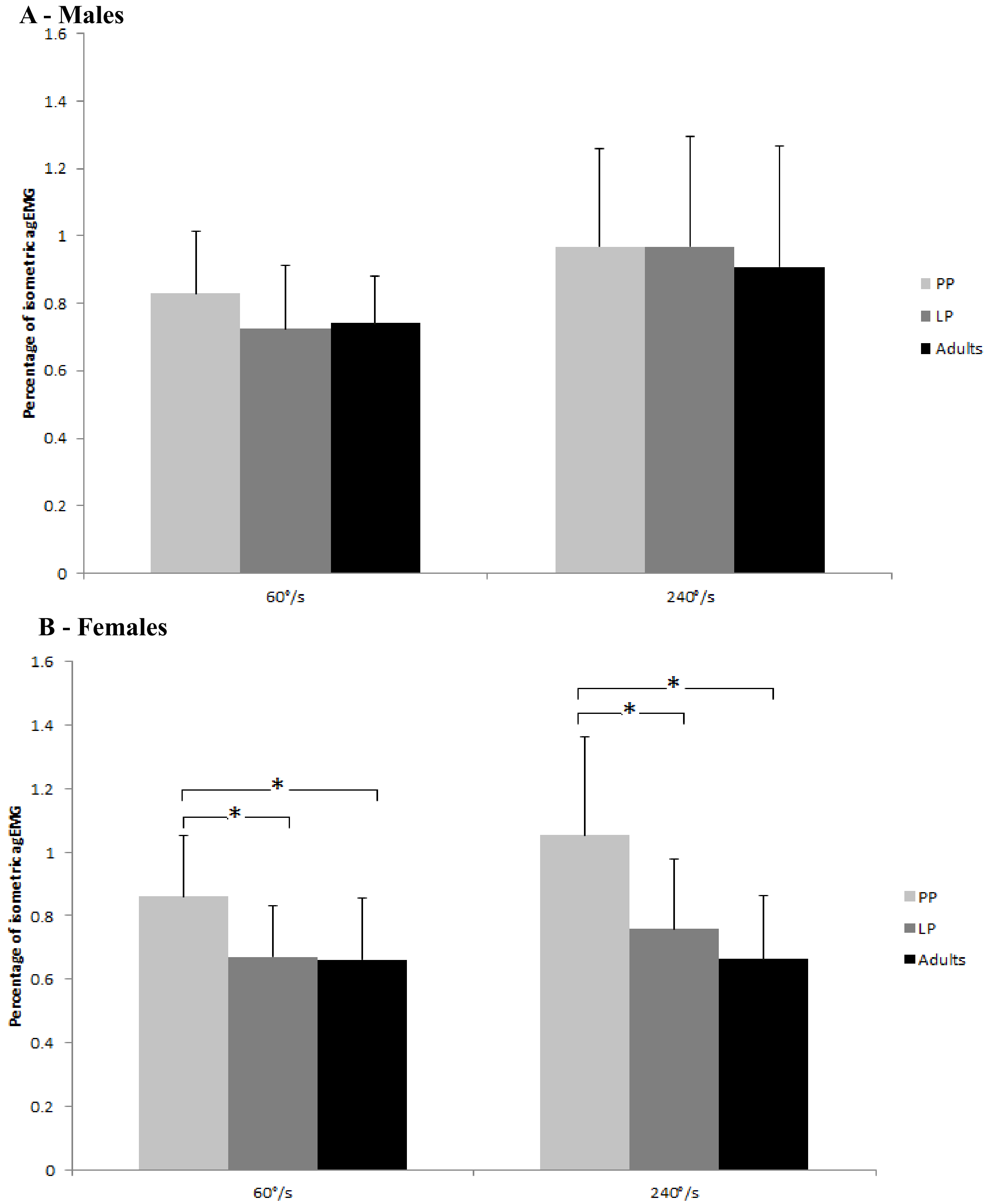


Figure 4.7:A - Proportion of isometric agEMG actvity attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult males. B – Proportion of isometric agEMG activity attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult females. Significant main effects of maturity for 60°/s and 240°/s contractions (*p*<.001 and *p*<.01, respectively). Main effect of Sex (*p*<.05) and sex*maturity interaction (*p*<.05) for 240°/s contractions.

4.6 Antagonist Muscle Activity

A significant main effect of Velocity, $F(2,218) = 5.2$, $p<0.05$, was apparent for antagonist muscle activity where the average antagonist EMG amplitude was lower in the 60°/s isokinetic contractions compared to both the isometric and 240°/s isokinetic contractions (Table 4.3). Antagonist activity was similar between the isometric and 240°/s isokinetic contractions.

Table 4.3: Antagonist EMG activity. Values are presented as M ± SD.

	Males			Females			Effect
	PPm	LPm	Am	PPf	LPf	Af	Maturity effect (p<.01), Velocity effect (p<.01)
AntEMGiso (mV)	0.016 ± 0.005	0.018 ± 0.008	0.012 ± 0.003	0.020 ± 0.011	0.016± 0.005	0.011 ± 0.007	
AntEMG60 (mV)	0.015 ± 0.005	0.014 ± 0.007	0.012 ± 0.005	0.018 ± 0.011	0.014 ± 0.008	0.009± 0.006	
AntEMG240 (mV)	0.016 ± 0.005	0.017 ± 0.005	0.015 ± 0.008	0.020 ± 0.008	0.014 ± 0.006	0.013 ± 0.016	

4.7 Rate of Muscle Activation (Q_{30})

In absolute terms, there were no significant Sex, Maturity, or Velocity related differences regarding Q_{30}. However, once Q_{30} was normalized to peak EMG amplitude, a Sex-by-Velocity interaction was found, $F(2,218) = 6.5$, $p<0.05$. That is, in the fast isokinetic contractions, females had significantly greater values compared with males. A main effect of maturity was also found, however no significant differences were revealed from the post hoc analysis.

Table 4.4: Normalized Q^{30}. Values are presented as M ± SD.

	PPm	LPm	Am	PPf	LPf	Af	Sex*Velocity interaction (p<.05)
Q^{30} Iso (mV*s/mV)	5.0 ± 2.5	5.4 ± 2.8	3.6 ± 1.8	4.9 ± 3.2	5.3 ± 2.3	4.3 ± 1.8	
Q^{30} 60 (mV*s/mV)	5.3 ± 3.5	5.7 ± 2.6	5.8 ± 4.5	4.6 ± 2.2	6.7 ± 2.9	5.4 ± 2.8	
Q^{30} 240 (mV*s/mV)	4.2 ± 2.4	5.0 ± 2.9	3.9 ± 2.0	5.0 ± 2.9	7.6 ± 4.3	5.6 ± 2.9	

With regards to isometric contractions, there was no significant correlation between absolute or normalized Q_{30} and absolute PrTD. However, significant positive correlations existed in regards to isokinetic contractions. Absolute Q_{30} was weakly correlated with normalized PrTD at all contraction velocities (r=.209, r=.279 and r=.400 for isometric, 60°/s and 240°/s, respectively). Normalized Q_{30} was only correlated with normalized PrTD during 60°/s isokinetic contractions. The results of an ANCOVA analysis reflected that Q_{30} is not a significant covariate in the sex- and maturity-related differences in normalized isometric or isokinetic PrTD.

4.8 Electromechanical-Delay (EMD)

As expected, a main effect of Maturity, $F(2,109)= 10.9$, $p<0.05$, was apparent with the EMD. The EMD for pre-pubertal children was significantly longer than both the late-pubertal and adult groups (Table 4.5). The EMD for the late-pubertal and adult groups were similar. A significant main effect of Velocity, $F(2,218)= 12.1$, $p<0.05$, was also found for EMD, reflecting a shorter EMD for 240°/s isokinetic contractions compared to both 60°/s isokinetic and isometric contractions.

Table 4.5: EMD. Values are presented as M ± SD.

	PPm	LPm	Am	PPf	LPf	Af	Maturity effect (P<.0001) Velocity effect (p<.0001)
EMDiso (ms)	72.7 ± 19.0	66.8 ± 11.5	62.4 ± 21.7	81.0 ± 24.0[a,b]	61.8 ± 16.4[a]	61.4 ± 16.7	
EMD60 (ms)	76.5 ± 29.1	63.8 ± 18.1	63.0 ± 23.8	74.7 ± 20.0	62.3 ± 19.0	62.0 ± 15.4	
EMD240 (ms)	65.7 ± 13.8	54.6 ± 17.0	53.3 ± 19.2	63.8 ± 15.1[b]	50.5 ± 14.7	58.6 ± 16.9	

[a] = significantly different than sex matched adult group, [b] = significantly different than sex-matched late-pubertal group, and [c] = significantly different than maturity matched-matched female group

A weak negative correlation was found between EMD and normalized PrTD for all contraction velocities (r= -.311, r= -.261, and r= -.295 for isometric, 60°/s and 240°/s contractions, respectively). The ANOCVA analysis revealed that EMD is a significant covariate for normalized PrTD during fast isokinetic contractions ($p<0.05$), and was approaching significance for isometric and slow isokinetic contractions ($p=0.06$ and $p=0.09$, respectively) as well.

4.9 Muscle Activation Efficiency

Figure 4.8A and B describes the activation efficiency in the three velocities of contraction for the males and females. Figure 4.9A and B describes the proportional decrease in efficiency relative to the isometric efficiency for the males and females. Only maturity-related pairwise differences within each velocity are indicated within the figure. All significant effects are listed in the figure's legend and explained below.

There was a significant main effect of Velocity, $F(2,218)= 12.5$, $p<0.05$, reflected by a higher efficiency for isometric compared to both isokinetic contractions. Efficiency for 60°/s and 240°/s isokinetic contractions was similar. A main effect of Maturity was also found, $F(2,109)= 3.9$, $p<0.05$, reflecting an increase in efficiency with maturity. Adults were significantly more efficient than pre-pubertal children, while late-pubertal children were more efficient than prepubertal children and less efficient than adults. A significant Maturity-by-Velocity interaction was also present, $F(4,218)= 4.2$, $p<0.05$, where efficiency was similar regardless of movement velocity in both pre- and late-pubertal children. However, in adults, isometric efficiency was significantly greater than both isokinetic contractions. For isometric contractions, efficiency significantly increased with maturity, as adults were significantly more efficient than both pre- and late-pubertal children. For isokinetic contractions at 60°/s, efficiency increased with maturity. However, the only pairwise comparison that was statistically significant was between adults and pre-pubertal children. Lastly, for isokinetic contractions at 240°/s, efficiency did not significantly change with maturity.

A significant main effect of Maturity was found, $F(2,109) = 5.9$, $p<0.05$, regarding differences in the proportional drop in muscle activation efficiency as movement velocity was increased from static to 240°/s (Figure 4.9A and B). Post hoc analysis revealed that adults experienced a greater drop in activation efficiency compared to both pre-pubertal and late-pubertal children. However, statistical significance was not reached in the adult to late-pubertal group comparison ($p=.052$). No main effects or significant interactions involving Sex were found.

A significant correlation was found between efficiency and normalized PT during isometric contractions ($r = .286$), fast isokinetic contractions ($r = .206$), and the correlations approached significance ($p=.06$, $r=.174$) for the slow isokinetic contractions. However, when included in an ANCOVA analysis, it was revealed that activation efficiency was not a significant covariate for the Sex and Maturity related differences in normalized isometric or isokinetic peak torque.

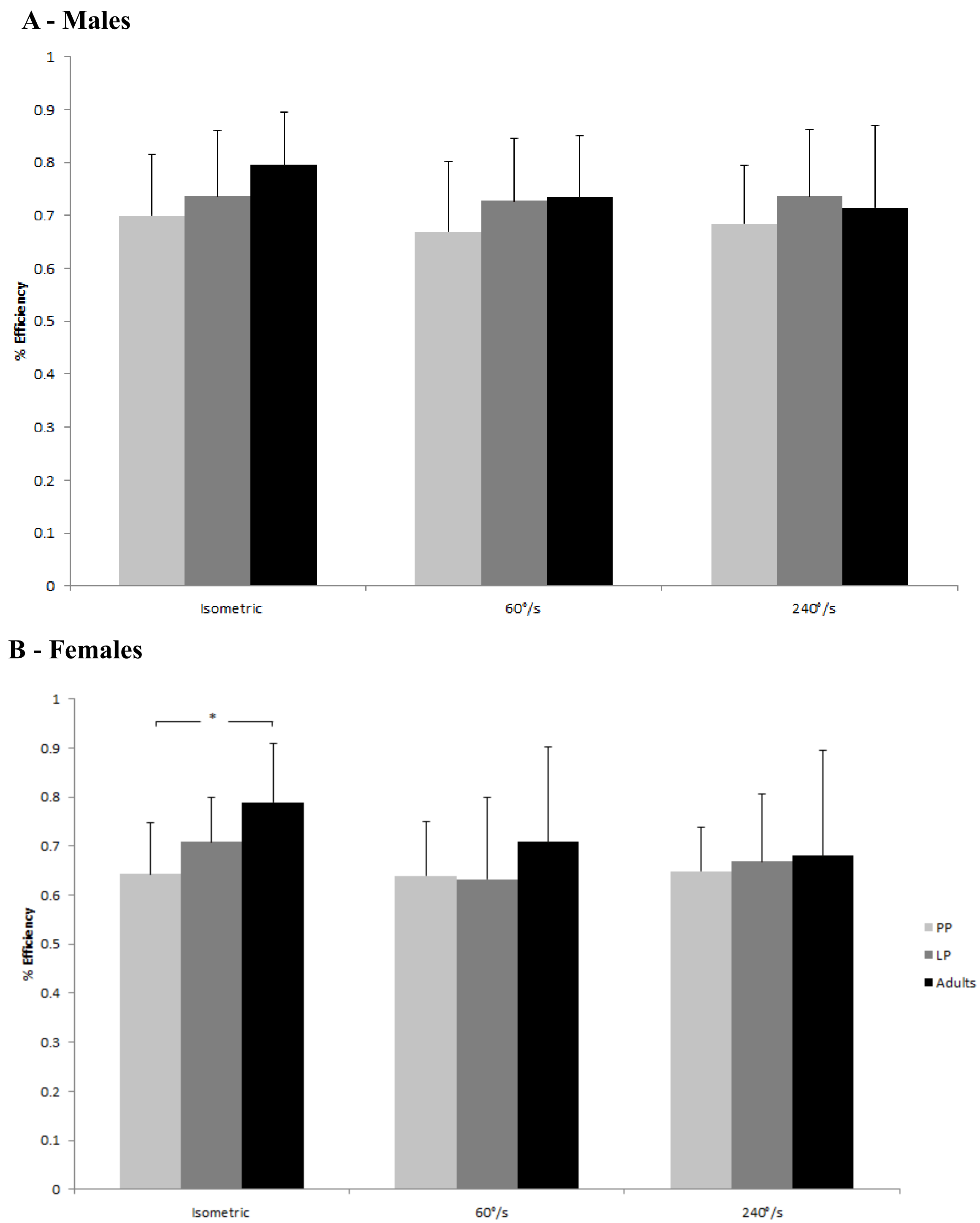
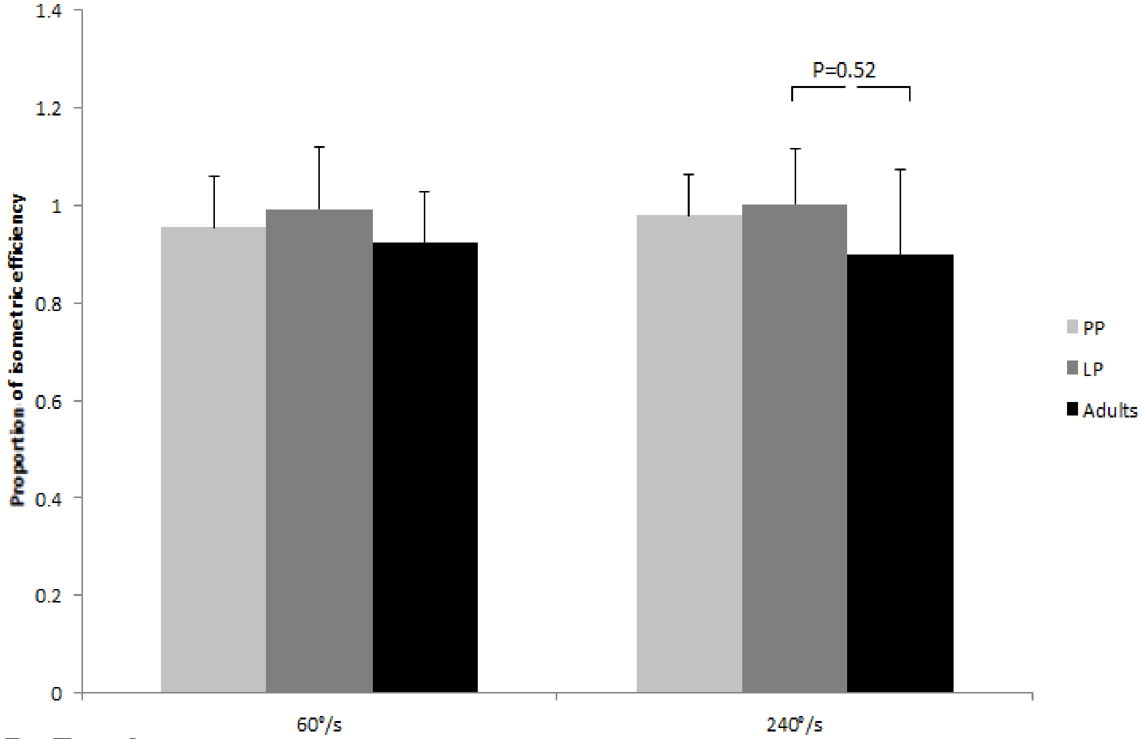


Figure 4.8:A - Knee extension activation efficiency of pre-pubertal, late-pubertal, and adult males during isometric, 60°/s isokinetic, and 240°/s isokinetic contractions. B – Knee extension activation efficiency of pre-pubertal, late-pubertal, and adult females during isometric, 60°/s isokinetic, and 240°/s isokinetic contractions. Significant main effects of maturity, and velocity ($p<.0001$). Significant maturity*velocity interaction ($p<.01$)

A - Males



B - Females

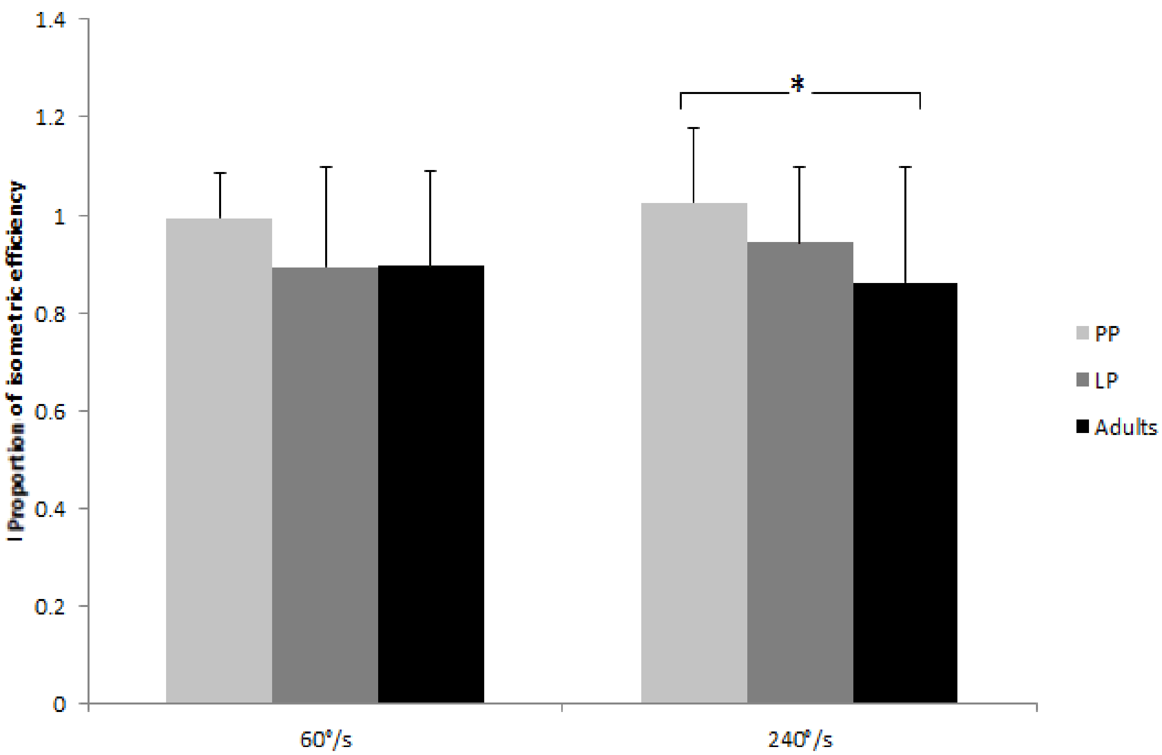


Figure 4.9:A - Proportion of isometric efficiency attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult males. B – Proportion of isometric efficiency attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult females. Significant main effects of maturity for 240°/s contractions (p<.01).

4.10 Coactivation

Figure 4.10A and B describes the coactivation for males and females in the three velocities of contraction. Figure 4.11 describes the males' and females' proportional increase in coactivation relative to the isometric coactivation. Only maturity-related pairwise differences within each velocity are indicated within the figures. All significant effects are listed in the figure's legend and explained below. A main effect of Velocity was found in the co-activation analysis ($F(2,218) = 9.2$, $p < .001$), reflecting lower coactivation values for isometric contractions compared to both 60°/s and 240º/s isokinetic contractions. Maturity by Velocity interaction, $F(4,218) = 3.2$, $p < 0.05$, was also found reflecting that pre-pubertal children had greater coactivation values compared to adults during only the isometric contractions.

A significant main effect of Maturity was found in the proportional increase in coactivation as movement velocity was increased from static to 60°/s and from static to 240°/s (Figure 4.11A and B). Post hoc analysis revealed adults had a greater proportional increase in coactivation compared to the pre-pubertal children during 60°/s contractions, and both pre- and late-pubertal children during 240°/s contractions.

A significant correlation was found between coactivation and normalized PT during isometric contractions (r= -.264) and it approached significance (p=.06, r= -.174) during the fast isokinetic contractions. However, when included in an ANCOVA analysis, it was revealed that coactivation was not a significant covariate for the sex- and maturity related differences in normalized isometric or isokinetic peak torque.

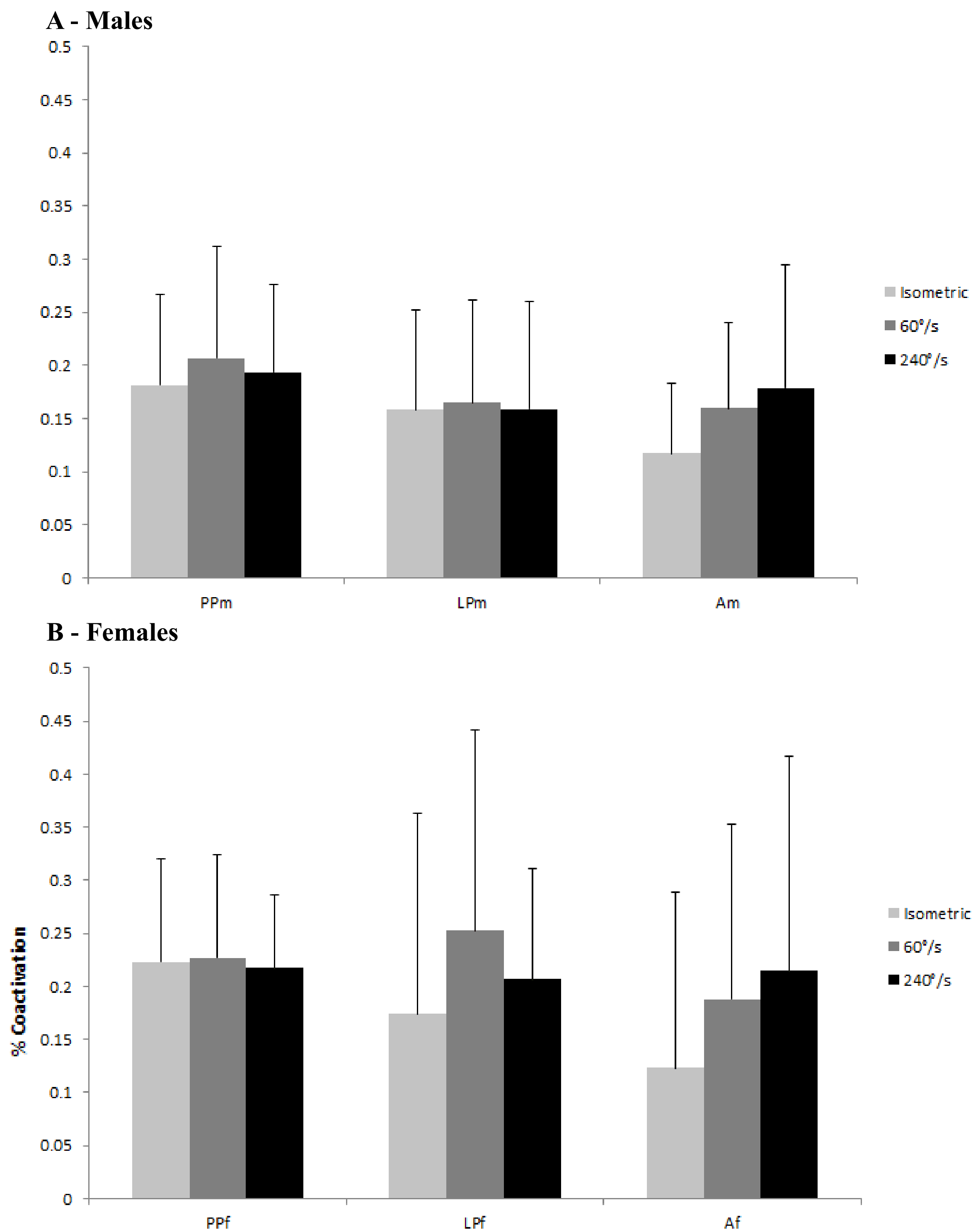


Figure 4.10:A - Knee extension coactivation of pre-pubertal, late-pubertal, and adult males during isometric, 60°/s isokinetic, and 240°/s isokinetic contractions. B – Knee extension coactivation of pre-pubertal, late-pubertal, and adult females during isometric, 60°/s isokinetic, and 240°/s isokinetic contractions. Significant main effect of Velocity ($p<.0001$). Significant maturity*velocity interaction ($p<.05$).

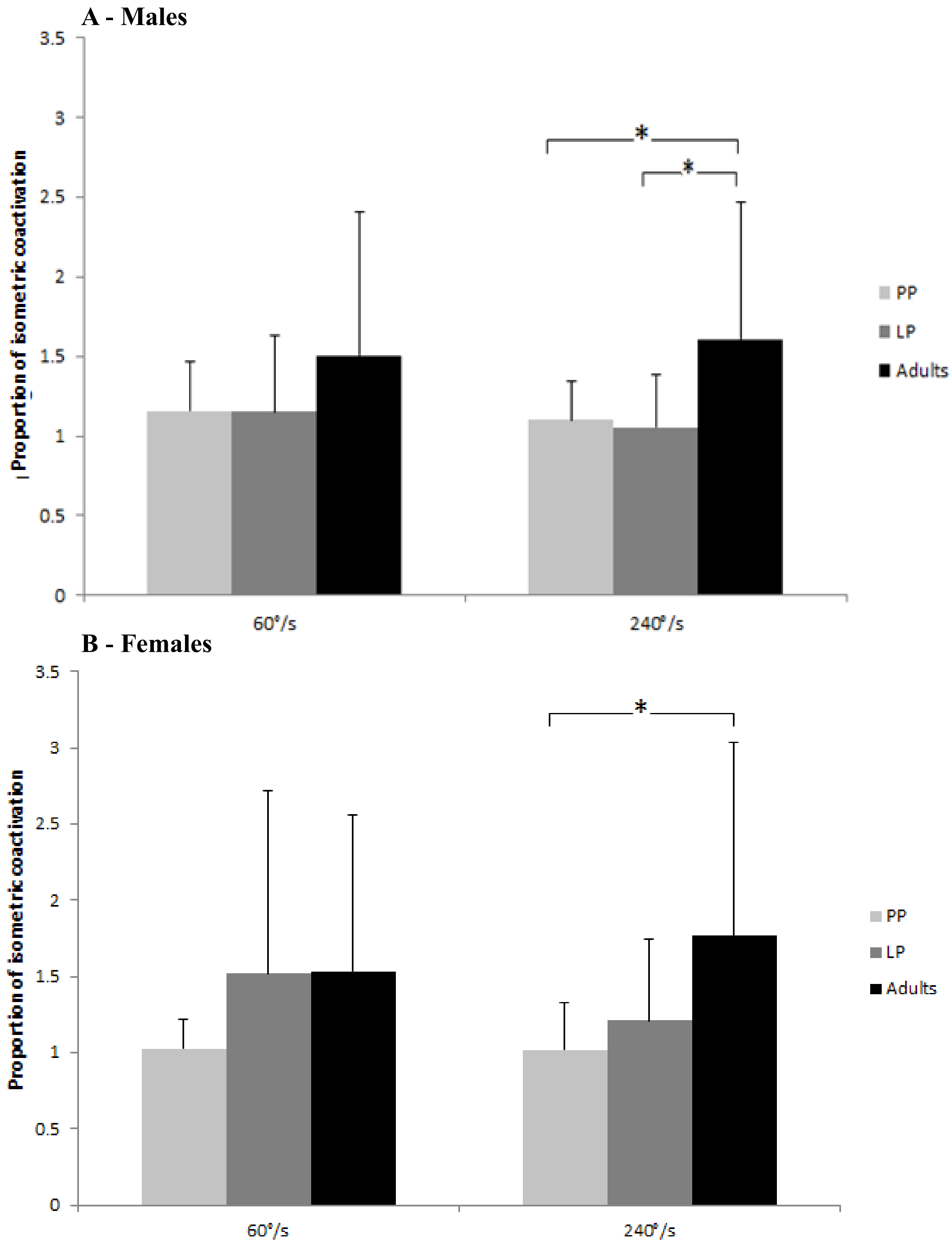


Figure 4.11:A - Proportion of isometric coactivation attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult males. B – Proportion of isometric coactivation attained during 60 and 240°/s contractions in pre-pubertal, late-pubertal, and adult females. Significant main effects of maturity for 60 and 240°/s contractions (*p*<.05 and *p*<.001, respectively).

4.11 Attainment of Target Velocity

There was no main effect of Sex on whether the participant could attain the isokinetic velocity during the 240°/s contraction. However, a main effect of Maturity was found, $\chi^2(2, N=115) = 42.9$, $p<0.05$, reflecting that a significantly greater percentage of late-pubescent's and adults were able to attain the target velocity compared to the pre-pubertal children.

<u>Table 4.6: Attainment of target velocity</u>. Values are presented as M ± SD.

	PPm	LPm	Am	PPf	LPf	Af	Maturity effect (p<.001),
Reach 240	5%[a,b]	53%	79%	3%[a,b]	64%	47%	

[a] = significantly different than sex matched adult group, [b] = significantly different than sex-matched late-pubertal group, and [c] = significantly different than maturity matched-matched female group

CHAPTER 5: DISCUSSION

The objective of this study was to compare maximal isometric and isokinetic strength and performance, along with pattern of muscle activation during knee extension in prepubertal, late-pubertal, and adult males and females. Our main results showed that adults were stronger and had higher RTD when expressed both in absolute values and relative to quadriceps CSA when compared to prepubertal children. The higher PT was accompanied by a higher muscle activation efficiency in the adults, compared to prepubertal children for all contraction types. All maturity groups experienced a drop in peak torque, RTD, and activation efficiency with increases in movement velocity. However, the adults generally experienced a proportionately greater drop in these values compared to pre-pubertal children. This was especially apparent in the fast isokinetic velocity. The current study is the first to examine the effects of movement velocity with the inclusion of EMG measures in such an inclusive sample population. EMD was significantly longer in children compared to adolescents and adults for all contraction velocities, and EMD was shorter in all groups for fast isokinetic contractions compared to isometric and slow isokinetic contractions. While the maturation differences in EMD have been suggested in previous studies (Asai & Aoki, 1996; Falk, Brunton et al. 2009; Falk, Usselman et al. 2009, Cohen et al. 2012), the finding of an effect of movement velocity on EMD is unique and requires further investigation. No clear pattern was found regarding the rate of muscle activation (normalized Q_{30}). Sex-related differences in absolute peak torque and RTD were apparent by late-puberty and were amplified in adulthood. However, when values were expressed relative to quadriceps CSA, sex-related differences were also apparent in the pre-pubertal children as males had greater strength than females. This finding was unique as many studies (De Ste Croix et al. 2002;

Ramos et al. 1998; Barber-Westin, Noyes, & Galloway, 2006; Sunnegardh et al. 1988) have not found sex-related differences in PT among pre-pubertal children. Lastly, it was noted that most of the children and even the women were unable to attain a velocity of 240°/s. That is, their RTD was insufficient to attain the required velocity, possibly reflecting lower explosive contractile capabilities in such groups.

5.1 Peak Torque

As expected, in the males, isometric and isokinetic peak torque significantly increased with maturity. This finding is consistent with the large body of available literature (Asmussen, 1973; Bassa et al. 2001; Camic et al. 2010; De Ste Croix et al. 2003; Falk, Usselman et al. 2009; Kanehisa et al. 1994; Wiggin et al. 2006; Bouchant, Martin, Maffiuletti, & Ratel, 2011). However, our female sample did not follow the same pattern as the males (Figure 4.1). While absolute isometric peak torque significantly increased with maturity, isokinetic peak torque at 60º/s and 240 º/s plateaued after late-puberty in the females.

When isometric and isokinetic peak torque was normalized to quadriceps cross-sectional area there was no longer a significant difference between late-pubertal children and adults which suggests that the increase in strength after puberty is mainly due to increases in muscle size. In fact, after normalizing for mCSA, peak torque tended to be lower in women compared with adolescent girls, although this pattern was significant only in the fast isokinetic velocity (Figure 4.2). Only one other study to the authors' knowledge (De Ste Croix, Armstrong, & Welsman, 1999) has investigated isokinetic knee extension peak torque (30, 60, 90 and 120°/s) in a female population that includes a late-pubertal and adult comparison. They also found a plateau in absolute peak isokinetic torque after the age of 14 in females. Our results in males are in agreement with previous studies, which also found lower CSA-normalized isometric torque in pre-pubertal children compared with adults in various muscle groups (Falk, Usselman et al. 2009; Halin et al. 2003; Kanehisa et al. 1994; Grosset et al. 2008; Davies, White, & Young, 1983; Kanehisa et al. 1995). Hence, our results support the notion that factors other than differences in muscle size are responsible for the differences in strength between pre-pubertal children and late-pubertal children or adults. As discussed below (see section 5.2), one of these factors may be related to muscle activation efficiency, or coactivation.

In agreement with a review by Blimke (1989), sex-related differences in absolute and normalized isometric peak torque were apparent in late-puberty and adulthood as males were stronger then maturity-matched females. This sex-related difference is primarily a result of a greater increase in body size and muscle mass in males during puberty. On the other hand, data from isokinetic studies have provided conflicting results regarding the age or maturity status at which sex-related differences appear. De Ste Croix et al. (2002) and Ramos et al. (1998) had boys and girls between the ages of 10-14 perform isokinetic knee extensions at multiple velocities and failed to find any sex-related differences in absolute peak torque at any velocity. It is possible that their participants, as a group, were too young to exhibit sex-related differences in strength. Barber-Westin, Noyes, & Galloway (2006) found sex differences in isokinetic knee extension peak torque at high velocities (300°/s) between 14 year-old boys and girls, where the boys were significantly stronger. In our study, we did not find any sex-related differences in isokinetic peak torque until adulthood. A major difference between the current study and that of Barber-Westin et al., (2006) is that the sample of the latter was comprised of athletes, while our study did not include any competitive athletes.

Moreover, Barber-Westin et al., (2006) found sex-differences during 300º/s isokinetic contractions, where our protocol, and Ramos et al., (1998) did not have contractions exceeding 240º/s. Therefore, it may be that sex-related differences in isokinetic torque in adolescents are apparent only during very fast isokinetic velocities.

Sunnegardh et al. (1988) failed to find sex-differences in CSA-normalized knee extension between 8 and 13 year-old children. However, higher strength in boys was observed during isokinetic knee flexion, elbow flexion, and elbow extension at 20, 90, and 120º/s. CSA was calculated from measurements of thigh circumference and skin folds in this study. Likewise, De Ste Croix et al. (2002), who used MRI to measure muscle CSA, did not find any sex-related differences in CSA-normalized torque in 10, 11, 12, or 14 year-old children when performing isokinetic knee extensions at 30, 60, 90, 120 and 180º/s. An explanation as to why there was a sex-difference in normalized peak torque in our pre-pubertal group is not readily available. Other studies are needed in order to validate at what stage sex-differences appear in CSA-normalized isometric and isokinetic peak torque.

Few studies to the author's knowledge have investigated the differences in strength between children and adults as contraction velocity is manipulated (Kanehisa et al. 1994; Bassa et al. 2001; Bassa et al. 2005). Bassa et al., (2001) found significant decreases in torque between 45º/s, 90º/s, and 180º/s isokinetic knee extensions in 6-12 year-old boys. Our results support these findings and extend them to a wider age range, as well as to females. Our findings also suggest that as maturity increases, the effects of increasing contraction velocity are amplified in that the proportion of torque decrease was greatest in the adults. This trend was similar in both males and females. It was expected that a greater decrease in torque with increasing velocity would be observed in the pre-pubertal children, reflecting their lower explosive strength (rate of torque development). However, this was not the case. A partial explanation for our finding is related to the calculated muscle activation efficiency discussed below. However, future studies are needed to elucidate other reasons for this phenomenon.

5.2 Agonist Activity at peak torque

As EMG amplitude is affected by numerous factors, including muscle size, skinfold thickness, and temperature (De la Barrera & Milner, 1994), the discussion below focuses on the change in agonist activity with the increase in movement velocity (i.e., only on within-subject effects). The highest agonist amplitude was observed during isometric contractions. Surprisingly, agonist EMG was higher during the fast 240º/s contractions, compared with the slower 60º/s contractions. However, there was a maturity-by-velocity interaction, reflecting that while both the pre-pubertal and late-pubertal groups had more agonist activity in the 240º/s versus the 60º/s, the adults had similar values for both isokinetic contractions. In fact, in the pre-pubertal children there was no difference in agonist activity between isometric and fast isokinetic contractions.

Overall, the adults experienced the greatest impact to their agonist activity values from altering contraction velocity. A possible explanation may be related to the previously described lower activation deficit in adults during isometric contractions (Blimke, 1989; Grosset, 2008; O'Brien et al. 2009). That is, it is possible that since adults generally use a greater proportion of their available motor pool, they have the potential to experience the greatest drop in agonist EMG activity. The greater proportionate drop of agonist EMG activity in adults compared to children as contraction velocity increased (Figure 4.7) may partially explain the greater proportionate drop in peak torque experienced by adults when contraction velocity was increased. Future studies needed to examine reasons as to why adults EMG activity are impacted by contraction velocity to a greater extent compared to children.

5.3 Muscle Activation Efficiency and Coactivation

Our measure of muscle activation efficiency was calculated as the difference between the agonist and antagonist activity, relative to the sum of the two. A greater value reflects a more efficient activation pattern, while a low number reflects a less efficient activation pattern. Similarly, coactivation reflects the amount of antagonist activity relative to the agonist activity. Therefore, a lower value represents a more efficient activation pattern.

No difference in activation efficiency or coactivation was observed between males and females. Overall, efficiency tended to be the greatest for isometric contractions, while there was no difference in efficiency between the isokinetic contractions. There was also a trend for activation efficiency to increase with maturity in isometric and slow isokinetic contractions, but not in the fast isokinetic movement. In adults, efficiency decreased (and coactivation increased) with an increase in velocity. This was not apparent in the children. This drop in efficiency matches the corresponding drops in peak torque and rate of torque development seen in the adult groups, suggesting that adults activate their muscles differently for isometric contractions, than they do for dynamic contractions. The drop in efficiency in adults from an isometric to fast isokinetic contraction was predominately due to a fall in the agonist EMG activity (rather than an increase in the antagonist EMG activity), as described earlier. A possible reason for this greater drop in the adults maybe that activation efficiency in children was relatively low to begin with during the isometric contractions and therefore, the decrease in efficiency was minimal in the isokinetic contractions. The children's lower efficiency in the isometric contraction may be due to activation of a lower proportion of their agonist motor units. Although there was a significant correlation between activation efficiency and normalized peak torque (r=.286 for isometric contractions), there is still a maturational effect on CSA-normalized peak torque after activation efficiency is taken into account, indicating that factors other than differences in activation efficiency contribute to the differences in strength between children and adults. The pattern of maturity and sex effects on coactivation was similar to these effects on efficiency. However, coactivation has been used more frequently in the literature. Therefore, the following paragraph compares our coactivation results to the available literature.

While most studies suggest that there are no age-related differences in coactivation during isometric contractions (Falk, Brunton et al., 2009; Falk, Usselman et al. 2009; Kellis & Unnithan, 1999; Bassa et al. 2005), few studies have investigated coactivation during dynamic contractions and how coactivation is changed with increases in contraction velocity. Bassa et al., (2005) had pre-pubertal and adult males perform isokinetic knee extensions at 45, 90, and 180°/s. Although they failed to find any age-related difference in coactivation, they found that coactivation significantly increased as isokinetic velocity increased in both groups. In the present study, coactivation increased with increasing velocity only in the adult groups. Among children, coactivation was higher in both isokinetic compared with isometric contractions, with no difference between slow and fast isokinetic contractions. Similar to Bassa et al. (2005) and Kellis and Unnithan (1999), we did not find any difference in coactivation between males and females. Additionally, there were no apparent differences between maturity groups in coactivation during the isokinetic contractions. However, unlike previous findings, we observed a pattern of decreased coactivation with maturity during the isometric contractions (Figure 4.6). Lambertz et al. (2003) and Grosset et al. (2008) examined coactivation in adults and prepubertal children during maximal and sub-maximal plantar flexion. While they did not find a significant difference in coactivation between the groups during maximal contractions, using linear regression analysis, their data suggest age-related decreases in coactivation. Therefore, it is likely that age-related differences in coactivation are dependent upon muscle action and possibly contraction velocity. Much of the discrepancy that exists regarding age and sex-related differences in coactivation within the literature may be partly explained by the several different methods utilized in order to calculate coactivation. More studies are needed to investigate age-related differences in knee extension coactivation, more specifically in females, and how much of an impact the potential differences have on the associated strength-related differences.

5.4 Rate of torque development

As expected, isometric and isokinetic peak rate of torque development significantly increased with maturity in males, while it plateaued after late-puberty in females. These findings are in line with previous studies reporting greater RTD in adults vs. children (males and females) during isometric elbow flexion (Asai & Aoki, 1996; Falk, Brunton et al., 2009; Falk, Usselman et al., 2010, Going et al., 1987), and knee extension (Cohen et al., 2010). Our findings demonstrate that the maturity-related increase in RTD is apparent also in isokinetic slow and fast contractions. Previous studies which examined RTD in children and adults did not include an adolescent group, nor did they examine isokinetic contractions.

Further, there is only one study which examined RTD in girls compared with women (Falk, Brunton et al., 2009). The present study extends previous findings, demonstrating that, RTD increases from pre- to late-puberty but unlike in males, it does not increase further in women (Asai & Aoki, 1996; Falk, Brunton et al., 2009; Falk et al., 2009b; Going et al., 1987; Grosset et al., 2005).

Since PrTD is affected by muscle size (as is maximal strength), PrTD was normalized to muscle CSA, as previously reported by others (Bell & Jacobs, 1986; Suetta et al. 2004). Once PrTD was normalized to qCSA, the values of the men and late-pubertal boys were no longer significantly different (Figure 4.4a), indicating that the age-related differences in absolute PrTD are predominately due to differences in muscle size. However, both groups still had significantly higher normalized PrTD compared to the pre-pubertal boys. Similarly, normalized RTD was greater in the LP girls and women compared with the PP girls. However, unlike the males, there was a pattern of decreased RTD in women compared with the LP girls (Figure 4.4b). Explanatory factors for this apparent decrease in women are unclear.

Sex–related differences in peak rate of torque development were examined by Bell and Jacobs (1986), who found that adult men had significantly greater PrTD compared to women during isometric elbow flexion. No studies to the authors' knowledge have investigated sex-related differences in adolescents or young children during isometric or isokinetic contractions. Our results suggest that sex-related differences in both isometric and isokinetic PrTD do not occur until adulthood where men have significantly greater values than women. Interestingly, after PrTD was normalized to mCSA, males had greater PrTD at all contraction velocities when compared to females in all three maturity groups. These findings are in agreement with Bell and Jacobs (1986), who demonstrated higher PrTD in men compared with women, and extend their findings to demonstrate higher PrTD in males even at pre-puberty. This is the first study to demonstrate sex-related differences in PrTD in children.

PrTD significantly decreased as contraction velocity was increased in each sex and maturity group. PrTD is partially dependent on amount of torque generated, and since peak torque decreased with velocity, it was expected that PrTD would follow a similar pattern. However, this effect was maturity-dependent, as adults were impacted to a proportionately greater extent by the higher isokinetic velocity when compared to children (Figure 4.5). Again, a possible reason for this may have been that the children were not optimally activating their muscles during the isometric contractions and therefore the decrease in the isokinetic contractions was minimal. Future studies are needed to validate the changes in the differences in PrTD between children and adults as contraction velocity is manipulated.

5.5 Rate of Muscle Activation (Q_{30})

Q_{30} has been used as an indicator of the rate of increase in neural drive during a maximal contraction in previous studies (Gottlieb et al., 1989; Falk, Usselman et al., 2009; Gabriel & Boucher, 2000). Falk, Usselman et al., (2009), were the first to measure Q_{30} in children, reporting that during isometric elbow flexion and extension, men had significantly greater Q_{30} compared to boys. No such differences were observed in women versus girls (Falk, Brunton et al. 2009). Contrary to Falk, Usselman et al. (2009), we did not find any maturation effect on Q_{30} in males or in females. There is a possibility that the contradiction could be due to a difference in methods. Falk, Usselman et al. (2009) measured Q_{30} from an average EMG trace of ten contractions which were time-locked according to the onset of torque. This means that as the EMD varies between trials, the onsets of EMG activity between trials become further apart relative to the onset of torque. When an average trace for the agonist activity is then calculated, all the trials with above average EMD will include portions of 0 EMG activity into the average, artificially lowering the calculation for Q_{30}. Therefore, the value of their Q_{30} would have been heavily dependent on the amount of variability of the EMD for each of those contractions (i.e., the greater the variability of EMD, the lower the Q_{30} value). This would create a bias against the children as their strength data has been shown to have much greater variability compared to adults (Farpour-Lambert & Blimke, 2008; Falk et al. 2012), and may be a reason why Falk, Usselman et al. (2009b) found a maturational effect on Q_{30} and we did not.

While the influence of muscle activation on rate of torque development has been suggested in previous studies (Hakkinen & Komi, 1986; Corcos, Gottlieb, & Agarwal, 1989), we did not find any correlation between Q_{30} and RTD for isometric contractions and only a weak correlation during slow and fast isokinetic contractions when looking at our whole sample, r=0.23 and r=0.24 respectively. When the correlations were calculated within each group, the pre-pubertal children did not display a correlation between Q_{30} and PrTD. However, similar to Falk, Usselman et al. (2009), we found a weak correlation between normalized PrTD and Q_{30} for isometric contractions (r=.209), as well as for isokinetic contractions (r=.297 and r=.400 for 60 and 240 °/s, respectively). The rate of muscle activation, as determined by Q_{30}, does not appear to explain the maturity-related difference in PrTD and further studies are needed to investigate the validity of the Q_{30} as a measure of rate of neural activation in children and for different actions.

5.6 Electromechanical-Delay (EMD)

EMD mainly reflects muscle-tendon stiffness, although it can also be affected by excitation-contraction coupling, and muscle fibre conduction velocity (Halin et al. 2003; Cavagna & Komi, 1979). As expected, EMD decreased with maturity in both sexes. This finding has been shown in isometric contractions during elbow flexion (Asai & Aoki, 1996; Falk, Brunton et al. 2009; Falk, Usselman et al. 2009) and knee extension (Cohen et al. 2010). Asai and Aoki (1996) also demonstrated longer EMD in boys during dynamic elbow flexion. The unique contribution of our study to the literature in terms of EMD is the inclusion of the adolescent group in the analysis in which we found had similar values to adults.

One unique and unexpected finding in our study was that EMD was significantly shorter in the fast isokinetic contractions compared to the isometric contractions. We did not expect to see any effect of movement velocity on EMD since the EMD is calculated prior to any movement at all. As all participants were instructed to contract "as hard and as fast as possible," and equal encouragement was given for all contraction velocities, we do not believe a difference in effort played a role in the EMD difference between contraction velocities. Since the order of contractions was counter-balanced, fatigue cannot explain this finding either

A possible reason for these differences may be in the methods of determining the onsets of EMG activity and torque. In the current study, onset of EMG activity was determined when the activity exceeded two standard deviations of the baseline activity for more than 100ms, which are similar criteria to those used in other studies examining isometric contractions (Falk, Brunton et al., 2009; Falk, Usselman et al., 2009; Cohen et al., 2010). We observed in this study that EMG activity during isokinetic contractions tended to be lower than that during isometric contractions. This lower EMG amplitude may have resulted in a later detection of the EMG onset, resulting in a shorter EMD. Therefore, while these criteria have been successfully used for isometric contractions in previous studies, they may be inappropriate in in fast, dynamic contractions, in which EMG amplitude is relatively lower.

5.7 Attainment of Target Velocity

An interesting finding in our study is the low percentage of children who were able to attain the 240°/s velocity (Table 4.6). There are few studies which have investigated high velocity movements in children. Barrett and Harrison (2002) visually inspected an angle-time graph attained by boys and men during knee extension at 300°/s to ensure there was an isokinetic portion of the movement indicating that the desired velocity was reached. Since the authors did not report participants being unable to reach the velocity, it is assumed that everyone reached 300º/s. Kanehisa et al. (1994) compared children and adults during isokinetic contractions at 60, 180, and 300°/s. It is unclear whether they examined if participants actually reached the desired velocity as it was never reported. Wiggen et al. (2006), on the other hand, reported on 3587 children between the ages of 6-13 who performed isokinetic knee extensions at 60, 120, and 180º/s. They determined that most children under the age of 10 could not generate torque fast enough to attain an isokinetic velocity of 180º/s. Thus, our findings are in line with Wiggin et al (2006), and extend them to higher velocity and greater age range.

We utilized spatial and temporal criteria to determine whether the target velocity was attained and found that only approximately 4% of pre-pubertal children and 60% of late-pubertal children were able to attain the target isokinetic velocity of 240°/s. Furthermore, 20% of the men and 53% of the women could not attain the target velocity of 240º/s. A significant maturity effect was found, reflecting that adults have greater explosive contraction capabilities than children. The greater explosive capacity may be related to adults' hypothesized ability to better recruit and utilize their fast-twitch type II muscle fibres in the knee extensors (Dotan et al., 2012).

Findings from previous paediatric studies that include high velocity isokinetic contractions should be interpreted with caution as it is still unclear whether children are capable of attaining such velocities. Some measures can only be derived from an isokinetic portion within the movement. Future studies need to report how it was determined if isokinetic velocity was reached or not, and what proportion of the sample was able to attain the velocities.

Thus, it is possible that the apparently lower reduction in peak torque with increasing velocity in children compared with adults is an artefact of the fact that children did not actually perform the 240°/s. That is, their peak toque at the fast isokinetic contraction was attained at a lower velocity (~230°/s). In line with the force-velocity relationship, since the increase in velocity was lower in children compared with adults, their torque reduction was also lower.

CHAPTER 6: CONCLUSION

6.1 General Conclusions

During isometric and isokinetic knee extension, adults elicited greater absolute and normalized PT and PrTD when compared to the pre-pubertal children. Sex-related differences in absolute PT and PrTD occurred in during late-puberty and were augmented in the adult groups, however when PT and PrTD were normalized to mCSA, sex-related differences were apparent at all maturities reflecting higher values in males compared to females. Higher muscle activation efficiency was found in the adults, compared to prepubertal children for all contraction types. All maturity groups experienced a significant decrease in PT, PrTD, and activation efficiency with increases in movement velocity; however, the adults generally experienced a proportionately greater drop in these values compared to pre-pubertal children. This was especially apparent in the fast isokinetic velocity. As expected EMD significantly decreased with maturity, and no sex-related differences were apparent. No meaningful significant sex- or maturity related differences were found regarding rate of muscle activation measured by Q_{30}.

This study was designed in order to gather physiological data to further examine muscle strength and performance, along with some associated neuromuscular mechanisms in males and females of different maturities. The current study was the first to investigate the effects of sex and maturation on muscle strength and performance with EMG measures in children of different maturation stages with the inclusion of isokinetic contractions. However, the cross-sectional design of this study brings forth limitations and future research should include a longitudinal design in order to better understand the effects of growth and maturation on muscle strength and performance and neuromuscular functioning.

6.2 Limitations and future directions

One of the main purposes of this study was to compare muscle strength and performance during isometric and isokinetic contractions at 60 and 240°/s. However, most young children did not have an isokinetic portion to their movements during the 240°/s contractions. Thus, observed group differences in muscle function in this velocity should be interpreted with caution. However, since the velocity attained by the children was not much lower than the assumed 240°/s (~230°/s), we believe that the pattern of the response can still be compared. Future research is needed to determine maximal movement velocities in children during knee extension and other actions.

A factor that may significantly affect muscle strength and performance that was not measured in this study was fibre-type composition. Since this requires muscle biopsies, ethical approval for such assessments in paediatric populations are extremely rare.

Surface EMG is widely used in the assessment of muscle activation in studies examining both children and adults. However, the activity recorded from a surface electrode is a composite of both the underlying physiological processes that generate myoelectric energy and the multitude of factors that affect the characteristic of the recording (Kamen & Caldwell, 1996). In the current study, electrode placement was kept as consistent as possible between subjects. However, the location of the motor point in a given muscle varies between individuals. In addition, the same electrodes were used for both children and adults, and since muscle size varies greatly between these two groups, activity was essentially being recorded from a different proportion of muscle mass. This proportional difference could potentially affect inter-individual comparisons of EMG amplitude-related measures. In our analysis, we focused on the pattern of change in EMG amplitude within (not between) groups. Therefore, the proportional difference in EMG electrode field does not affect our conclusions. Furthermore, our measures of efficiency and Q_{30} were normalized to their respective peak EMG amplitude, thereby eliminating the effect of extraneous factors, including the disproportionate electrode field, on between-group comparisons.

As children go through puberty hormonal differences greatly vary between sexes. These differences may have a direct effect on the development of muscle strength and performance (Blimke, 1989). Therefore, future studies examining maturity and sex-related differences in muscle function could benefit from measurements of hormonal levels.

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Appendix A: Subject Checklist – Biodex **<u>Subject Checklist – Biodex</u>**

Subject name: ______________________________ Subject ID: ______________

Gender: M / F Dominant arm: R / L Dominant leg: R / L

<u>Test Order:</u> _____________ (Matrix number)

Visit # ________ Limb: _____________ Date: _____________________________

Extension / Flexion: Isometric Limb Weight N·m: __________

Isokinetic: _________ degrees/sec

Isokinetic: _________ degrees/sec Scaling (ft·lbs): _______

Isometric

Extension / Flexion: Isometric

Isokinetic: _________ degrees/sec Scaling (ft·lbs): _______

Isokinetic: _________ degrees/sec

Isometric

KNEE EXTENSION

Isometric - Pre

Trial #	Peak Torque N·m	OK	Trial #	Peak Torque N·m	OK
1			3		
2			4		

Isometric – Post

Trial #	Peak Torque N·m	OK	Trial #	Peak Torque N·m	OK
1			3		
2			4		

Isokinetic - °/s

Trial #	OK	Trial #	OK
1		5	
2		6	
3		7	
4		8	

Isokinetic - °/s

Trial #	OK	Trial #	OK
1		5	
2		6	
3		7	
4		8	

Appendix B: Anthropometric Measurements Data Collection Sheet

NAME: ________________________ TEST DATE (MM/DD/YYYY): _______________

ID NUMBER: _________ GENDER: M / F AGE: ________

DATE OF BIRTH (MM/DD/YYYY): _______________ DOMINANT ARM: R / L

SUBJECT HEIGHT (cm): __________ SEATED HEIGHT (cm): __________
(Table = 75.5

SUBJECT WEIGHT (kg): __________

BIA - BMI: __________ BIA – % BODY FAT: __________

THIGH LENGTH (cm): __________________________

TRIAL 1	TRIAL 2	TRIAL 3	MEDIAN

THIGH CIRCUMFERENCE (cm): ____________________________

TRIAL 1	TRIAL 2	TRIAL 3	MEDIAN

SKINFOLD MEASUREMENT (mm):

SITE	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4 (>1 mm diff)	MEDIAN
TRICEP					
SUBSCAP.					
BICEPS					

SUM OF SKINFOLDS (mm): SUM @2 S.F ____________

(2 Skinfold sites = Subscap+Tricep) % BODYFAT ___________

SKINFOLD MEASUREMENT OF THE THIGH

SITE	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4 (>1 mm diff)	MEDIAN
ANTERIOR					
POSTERIOR					
MEDIAL					
LATERAL					

SUM OF SKINFOLDS (mm):

SUM @4 S.F ___________

MUSCLE DIAMETER (mm)

MUSCLE	TRIAL 1	TRIAL 2	TRIAL 3	TRAIL 4	MEDIAN
VASTUS LATERALIS/ MEDIALIS/ RECTUS FEMORIS					

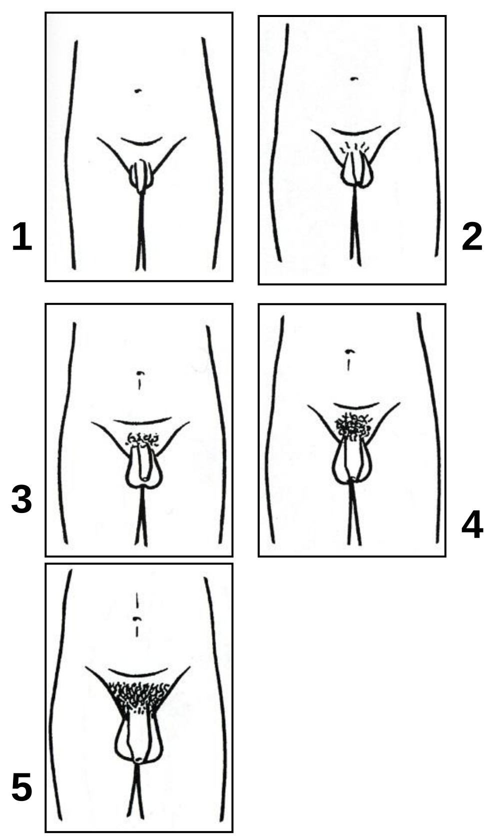
Appendix C: Pubertal Stage Questionnaire (Tanner, 1962)

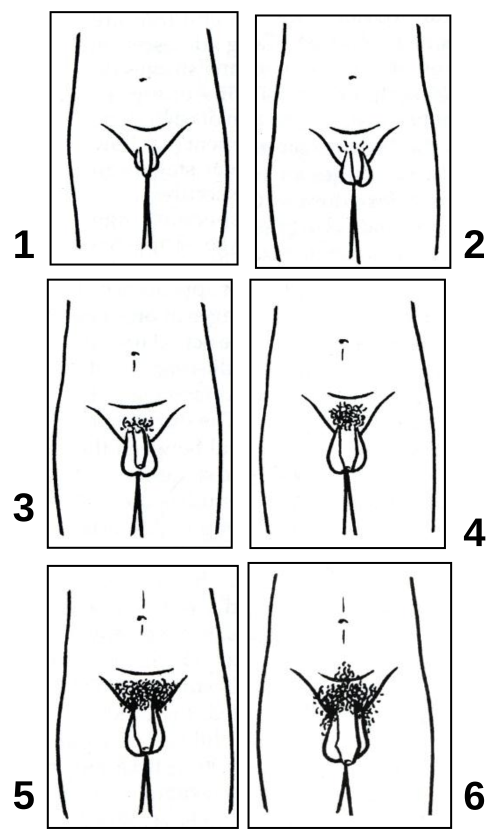
Male Pubertal Stage

This survey will be used to assess the maturational levels of the participant. For each photo choose the appropriate stage and place an X in the corresponding square.

ID: ______________________________ Date: ________________________

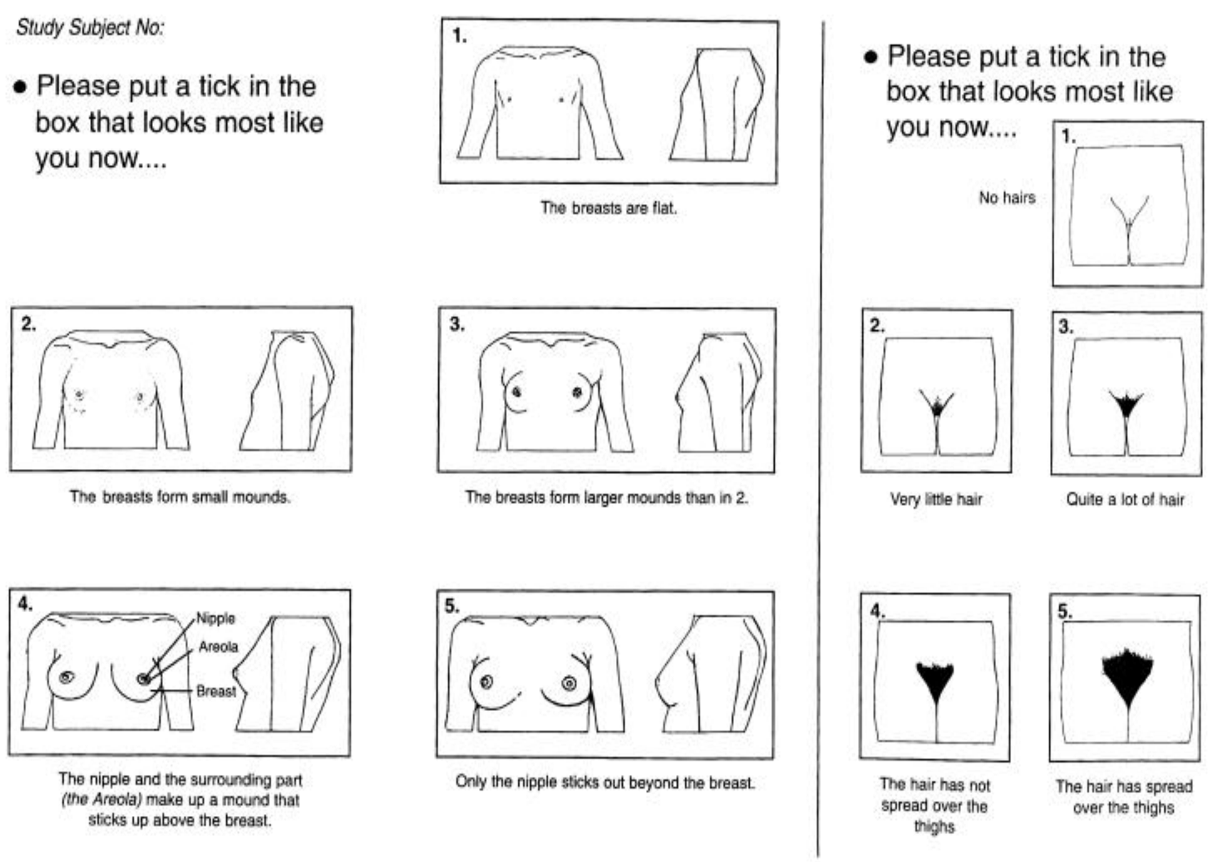
• Please circle the box that looks most like you		• Please look at the pubic hair only • Please circle the box that looks most like you





Female Pubertal Stage

Directions: You should choose only <u>one</u> of the stages shown below. One stage for Breast development and one stage for Pubic Hair development.



From Taylor et al, 2001.

Appendix D: Medical History Questionnaire

SUBJECT SCREENING AND MEDICAL HISTORY QUESTIONNAIRE

Name: ______________________________ DOB: ______________________________

Dominant Hand: ______________________ Dominant Leg: ______________________

Your responses to this questionnaire are confidential. If you answer "YES" to any of the following questions, please give additional details in the space provided and discuss the matter with one of the investigators. You may refuse to answer any of the following questions.

1. Have you ever had any major joint instability or ongoing chronic pain such as in the knee, back or elbow?
   YES NO
2. Are you currently taking any medication (including aspirin) or have you taken any medication in the last two days?
   YES NO
3. Have you taken any medication in the past six months?
   YES NO
4. Is there any medical condition with which you have been diagnosed and are under the care of a physician (e.g. asthma, diabetes, anorexia)?
   YES NO
5. Do you, or have you in the past, consumed any alcohol on a regular basis?
   YES NO
6. Do you, or have you in the past, smoked on a regular basis?
   YES NO
7. Are you, or have you in the past, engaged in any extreme diet?
   YES NO
8. Do you, or have you in the past, consumed any nutritional supplements (e.g. calcium, multi-vitamin) on a regular basis?
   YES NO
9. Do you, or have you in the past, engaged in physical activity on a regular basis?
   YES NO
10. Have you had any fractures? YES NO

11. **FEMALES ONLY:** Have you had your period? YES NO

Appendix E: Godin-Shepard Leisure Time Exercise Questionnaire

GODIN-SHEPHARD LEISURE-TIME EXERCISE QUESTIONNAIRE

1. Considering a **7-day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your **free-time** (write on each line the appropriate number)?

Times Per Week

(a) STRENUOUS EXERCISE (HEART BEATS RAPIDLY)
(i.e. running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling) _________

(b) MODERATE EXERCISE (NOT EXHAUSTING)
(i.e. fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing) _________

(c) MILD EXERCISE (MINIMAL EFFORT)
(i.e. yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking) _________

2. Considering a **7-day period** (a week), during your leisure-time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?

1. OFTEN	**2. SOMETIMES**	**3. NEVER/RARELY**
☐	☐	☐

Appendix F: Descriptive Statistics – Pre-Pubertal Males

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
Tanner	21.00	0.00	1.00	1.00	1.00	0.00	0.00
Maturity	21.00	0.00	1.00	1.00	1.00	0.00	0.00
Age	21.00	4.29	8.08	12.37	9.91	1.27	1.53
YearsPHV	21.00	2.78	-4.41	-1.63	-3.20	0.83	0.65
Height	21.00	32.60	125.50	158.10	140.26	8.76	73.16
Weight	21.00	22.60	24.70	47.30	35.96	6.58	41.26
PBF	21.00	29.60	3.00	32.60	16.59	7.46	53.00
BMI	21.00	9.50	14.54	24.03	18.19	2.38	5.38
LBM	21.00	15.90	20.89	36.79	29.11	4.46	18.91
ThighLeanCSA	21.00	53.92	68.18	122.09	92.42	14.65	204.42
MuscleDia	21.00	10.92	24.11	35.02	29.46	3.22	9.88
qCSA	21.00	5.07	4.56	9.63	6.89	1.49	2.12
ThighLength	21.00	24.40	25.00	49.40	31.29	5.11	24.82
ThighCirc	21.00	11.60	33.70	45.30	39.70	3.70	13.03
SFantThigh	21.00	36.90	7.60	44.50	18.20	8.69	71.99
SFpostThight	5.00	7.20	10.00	17.20	13.88	3.09	7.63
SFmedThigh	17.00	23.30	9.90	33.20	17.64	5.71	30.66
SFlatThigh	17.00	20.70	6.60	27.30	14.36	5.76	31.28
SFmeanThigh	21.00	35.77	8.73	44.50	18.23	8.38	66.82
Gsactivity	21.00	88.00	25.00	113.00	67.90	24.17	556.28
ISOPT	21.00	114.21	52.07	166.28	82.85	29.43	825.09
i60PT	21.00	75.73	36.28	112.00	60.11	18.12	312.68
i240PT	21.00	42.89	23.28	66.16	35.78	10.42	103.47
ISOPTcsa	21.00	14.98	7.74	22.71	12.19	3.92	14.60
i60PTcsa	21.00	9.26	6.04	15.30	8.87	2.45	5.72
i240PTcsa	21.00	5.67	3.37	9.04	5.30	1.50	2.13
Ptiso_60	21.00	0.47	0.06	0.53	0.25	0.12	0.01
PT60_240	21.00	0.42	0.18	0.60	0.39	0.10	0.01
Ptiso_240	21.00	0.41	0.29	0.70	0.55	0.11	0.01
ISOTtPT	21.00	2074.00	770.00	2844.00	1691.79	637.21	386700.26
i60TtPT	21.00	195.00	270.00	465.00	338.02	49.47	2331.01
i240TtPT	21.00	103.50	178.50	282.00	216.88	29.16	809.80
ISOPrTD	21.00	615.04	212.44	827.48	406.02	140.31	18750.21
i60PrTD	21.00	548.63	158.47	707.10	338.09	127.47	15475.23
i240PrTD	21.00	261.14	156.01	417.15	268.13	63.69	3862.85
ISOPrTDcsa	21.00	76.47	36.56	113.04	60.12	19.92	377.93
i60PrTDcsa	21.00	68.27	28.32	96.59	49.96	17.91	305.39
i240PrTDcsa	21.00	45.35	19.10	64.45	40.44	12.19	141.46

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
PrTDiso_60	21.00	0.55	-0.07	0.47	0.16	0.16	0.02
PrTD60_240	21.00	0.71	-0.17	0.54	0.15	0.23	0.05
ISOTtPrTD	21.00	60.00	53.00	113.00	82.92	15.90	240.76
i60TtPrTD	21.00	110.00	61.00	171.00	115.23	30.59	891.19
i240TtPrTD	21.00	32.67	48.00	80.67	63.22	10.05	96.21
ISOemd	21.00	92.50	39.50	132.00	72.65	18.90	340.24
i60emd	21.00	102.50	25.00	127.50	76.47	29.13	808.23
i240emd	21.00	53.33	43.00	96.33	65.67	13.78	180.84
ISOq30	21.00	9.6E-04	9.9E-05	1.1E-03	4.0E-04	2.5E-04	5.7E-08
i60q30	21.00	1.4E-03	1.4E-04	1.5E-03	3.8E-04	3.0E-04	8.7E-08
i240q30	21.00	5.1E-04	8.5E-05	5.9E-04	3.1E-04	1.4E-04	1.8E-08
ISOq30N	21.00	10.94	1.53	12.47	4.98	2.54	6.15
i60q30N	21.00	12.76	1.78	14.54	5.28	3.52	11.79
i240q30N	21.00	9.96	1.58	11.54	4.19	2.36	5.28
ISOagEMGpt	21.00	1.4E-04	4.5E-05	1.8E-04	1.0E-04	3.6E-05	1.2E-09
i60agEMGpt	21.00	9.5E-05	4.6E-05	1.4E-04	8.1E-05	2.8E-05	7.4E-10
i240agEMGpt	21.00	1.4E-04	3.5E-05	1.7E-04	9.5E-05	3.5E-05	1.2E-09
ISOantEMGpt	21.00	2.2E-05	1.0E-05	3.2E-05	1.6E-05	5.3E-06	2.7E-11
i60antEMGpt	21.00	1.6E-05	7.3E-06	2.3E-05	1.5E-05	4.9E-06	2.3E-11
i240antEMGpt	21.00	1.5E-05	9.8E-06	2.5E-05	1.6E-05	5.1E-06	2.4E-11
ISOEffPT	21.00	0.43	0.43	0.86	0.70	0.11	0.01
i60EffPT	21.00	0.46	0.37	0.83	0.67	0.13	0.02
i240EffPT	21.00	0.45	0.42	0.87	0.68	0.11	0.01
ISOCoact	21.00	0.33	0.08	0.40	0.18	0.09	0.01
i60Coact	21.00	0.39	0.09	0.48	0.21	0.10	0.01
i240coact	21.00	0.34	0.07	0.41	0.19	0.08	0.01

Appendix G: Descriptive Statistics – Late-Pubertal Males

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
Tanner	17.00	2.00	4.00	6.00	4.41	0.71	0.48
Maturity	17.00	0.00	2.00	2.00	2.00	0.00	0.00
Age	17.00	4.81	11.68	16.50	13.64	1.45	1.98
YearsPHV	17.00	4.13	-2.27	1.87	-0.14	1.31	1.62
Height	17.00	36.10	144.40	180.50	165.34	9.40	83.12
Weight	17.00	61.50	33.00	94.50	57.46	16.23	247.86
PBF	17.00	22.80	7.60	30.40	15.72	7.43	51.99
BMI	17.00	14.82	15.83	30.65	20.75	4.28	17.21
LBM	17.00	37.43	28.85	66.28	46.08	9.63	87.24
ThighLeanCSA	17.00	136.79	88.39	225.18	138.15	38.38	1386.12
MuscleDia	17.00	23.12	27.50	50.62	34.83	6.73	42.60
qCSA	17.00	14.18	5.94	20.12	9.86	4.17	16.36
ThighLength	17.00	14.50	31.00	45.50	37.79	3.13	9.20
ThighCirc	17.00	27.60	36.80	64.40	47.33	6.83	43.88
SFantThigh	17.00	30.40	8.00	38.40	17.58	8.22	63.55
SFpostThight	3.00	9.10	10.00	19.10	13.87	4.70	14.74
SFmedThigh	17.00	35.60	9.00	44.60	23.23	9.91	92.47
SFlatThigh	13.00	22.60	6.40	29.00	16.12	6.96	44.77
SFmeanThigh	17.00	26.40	9.27	35.67	19.14	7.94	59.35
Gsactivity	17.00	113.00	0.00	113.00	59.59	33.50	1056.48
ISOPT	17.00	241.97	112.51	354.48	187.32	77.74	5688.08
i60PT	17.00	170.61	64.41	235.02	124.36	50.77	2426.24
i240PT	17.00	107.29	25.83	133.11	70.10	31.91	958.57
ISOPTcsa	17.00	16.14	14.51	30.65	19.40	4.56	19.56
i60PTcsa	17.00	11.43	8.72	20.16	12.88	3.24	9.88
i240PTcsa	17.00	8.76	3.51	12.27	7.26	2.27	4.87
Ptiso_60	17.00	0.34	0.20	0.54	0.33	0.09	0.01
PT60_240	17.00	0.26	0.37	0.62	0.44	0.07	0.01
Ptiso_240	17.00	0.29	0.53	0.82	0.63	0.07	0.01
ISOTtPT	17.00	2287.67	488.00	2775.67	1689.03	704.22	466749.83
i60TtPT	17.00	208.33	259.00	467.33	328.85	62.00	3618.11
i240TtPT	17.00	152.67	181.33	334.00	232.23	37.91	1352.71
ISOPrTD	17.00	1542.94	265.85	1808.79	873.18	441.40	183370.88
i60PrTD	17.00	1305.45	265.09	1570.54	732.44	364.56	125082.82
i240PrTD	17.00	765.86	214.18	980.04	472.67	231.73	50540.30
ISOPrTDcsa	17.00	122.01	36.17	158.18	89.57	32.72	1007.93
i60PrTDcsa	17.00	116.69	36.07	152.76	75.85	28.57	768.36
i240PrTDcsa	17.00	67.75	25.95	93.70	48.89	16.07	243.17

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
PrTDiso60	17.00	0.39	-0.01	0.38	0.14	0.12	0.01
PrTD60240	17.00	0.34	0.15	0.49	0.34	0.11	0.01
ISOTtPrTD	17.00	60.33	55.00	115.33	78.38	13.90	181.77
i60TtPrTD	17.00	120.33	78.00	198.33	119.47	32.15	973.03
i240TtPrTD	17.00	241.00	38.00	279.00	104.58	67.63	4304.36
ISOemd	17.00	41.33	45.33	86.67	66.82	11.48	124.07
i60emd	17.00	77.00	37.00	114.00	63.83	18.06	306.97
i240emd	17.00	61.50	24.50	86.00	54.56	17.04	273.37
ISOq30	17.00	1.5E-03	1.3E-04	1.6E-03	5.5E-04	4.0E-04	1.5E-07
i60q30	17.00	1.2E-03	1.5E-04	1.4E-03	4.7E-04	3.3E-04	1.0E-07
i240q30	17.00	1.8E-03	1.5E-04	2.0E-03	5.1E-04	4.5E-04	1.9E-07
ISOq30N	17.00	10.69	1.06	11.75	5.36	2.84	7.61
i60q30N	17.00	8.69	2.48	11.16	5.67	2.58	6.26
i240q30N	17.00	10.21	1.28	11.49	5.03	2.88	7.80
ISOagEMGpt	17.00	1.7E-04	4.4E-05	2.1E-04	1.3E-04	5.5E-05	2.8E-09
i60agEMGpt	17.00	1.3E-04	4.2E-05	1.8E-04	9.0E-05	3.8E-05	1.4E-09
i240agEMGpt	17.00	1.8E-04	5.0E-05	2.3E-04	1.2E-04	5.7E-05	3.0E-09
ISOantEMGpt	17.00	2.6E-05	8.9E-06	3.4E-05	1.8E-05	7.7E-06	5.6E-11
i60antEMGpt	17.00	2.3E-05	5.3E-06	2.8E-05	1.4E-05	6.7E-06	4.2E-11
i240antEMGpt	17.00	3.4E-05	5.4E-06	4.0E-05	1.7E-05	9.0E-06	7.6E-11
ISOEffPT	17.00	0.52	0.37	0.89	0.74	0.12	0.01
i60EffPT	17.00	0.52	0.33	0.85	0.73	0.12	0.01
i240EffPT	17.00	0.56	0.33	0.89	0.74	0.13	0.02
ISOCoact	17.00	0.41	0.06	0.47	0.16	0.09	0.01
i60Coact	17.00	0.42	0.08	0.50	0.16	0.10	0.01
i240coact	17.00	0.45	0.06	0.50	0.16	0.10	0.01

Appendix H: Descriptive Statistics – Adult Males

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
Tanner	14.00	0.00	6.00	6.00	6.00	0.00	0.00
Maturity	14.00	0.00	3.00	3.00	3.00	0.00	0.00
Age	14.00	4.75	19.40	24.15	21.79	1.68	2.63
YearsPHV	0	0	0	0	0	0	0
Height	14.00	26.00	167.60	193.60	182.04	6.61	40.52
Weight	14.00	33.80	71.50	105.30	86.09	11.13	115.08
PBF	14.00	24.80	8.00	32.80	19.31	7.04	46.05
BMI	14.00	10.80	21.10	31.90	25.97	2.86	7.57
LBM	14.00	26.97	55.55	82.52	69.49	8.26	63.36
ThighLeanCSA	14.00	85.61	177.80	263.41	204.28	25.03	581.58
MuscleDia	14.00	20.20	37.10	57.30	46.10	5.45	27.54
qCSA	14.00	14.98	10.81	25.79	16.91	4.04	15.13
ThighLength	14.00	40.80	3.70	44.50	36.37	9.79	88.95
ThighCirc	13.00	12.60	50.50	63.10	55.95	4.05	15.16
SFantThigh	14.00	30.60	6.00	36.60	18.13	9.03	75.70
SFpostThight	0.00	0.00	0.00	0.00	0	0	0
SFmedThigh	6.00	30.00	14.00	44.00	22.45	10.94	99.77
SFlatThigh	8.00	16.00	6.40	22.40	11.28	5.30	24.59
SFmeanThigh	14.00	28.40	8.20	36.60	18.52	9.00	75.26
Gsactivity	14.00	87.00	23.00	110.00	63.21	26.06	630.60
ISOPT	14.00	255.82	235.37	491.18	309.34	65.93	4036.12
i60PT	14.00	102.64	162.44	265.07	210.05	30.01	836.45
i240PT	14.00	105.08	54.09	159.16	109.08	35.65	1180.20
ISOPTcsa	14.00	18.39	12.25	30.63	18.94	4.68	20.37
i60PTcsa	14.00	13.97	7.98	21.94	13.02	3.49	11.31
i240PTcsa	14.00	7.94	3.36	11.30	6.78	2.71	6.82
Ptiso_60	14.00	0.31	0.17	0.48	0.31	0.11	0.01
PT60_240	14.00	0.39	0.35	0.74	0.49	0.12	0.01
Ptiso_240	14.00	0.39	0.45	0.85	0.64	0.13	0.01
ISOTtPT	14.00	2126.33	897.33	3023.67	2129.49	616.40	352804.43
i60TtPT	14.00	174.50	233.50	408.00	311.81	51.28	2441.92
i240TtPT	14.00	111.00	185.00	296.00	223.56	35.56	1174.41
ISOPrTD	14.00	1330.24	703.11	2033.34	1405.11	380.85	134686.46
i60PrTD	14.00	1045.60	848.16	1893.76	1303.22	315.01	92145.60
i240PrTD	14.00	1007.39	322.95	1330.34	751.08	293.94	80231.23
ISOPrTDcsa	14.00	103.67	32.85	136.52	87.36	29.51	808.38
i60PrTDcsa	14.00	86.09	41.24	127.33	80.39	24.44	554.47
i240PrTDcsa	14.00	55.56	20.04	75.60	46.12	19.10	338.70

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
PrTDiso60	14.00	0.61	-0.26	0.36	0.05	0.15	0.02
PrTD60240	14.00	0.49	0.30	0.79	0.43	0.15	0.02
ISOTtPrTD	14.00	59.00	60.33	119.33	89.95	17.63	288.53
i60TtPrTD	14.00	69.00	76.00	145.00	103.04	18.72	325.29
i240TtPrTD	14.00	181.50	61.00	242.50	140.14	56.44	2957.44
ISOemd	14.00	62.33	30.00	92.33	62.44	21.68	436.58
i60emd	14.00	100.50	24.00	124.50	62.96	23.76	524.02
i240emd	14.00	67.00	28.00	95.00	53.33	19.16	341.01
ISOq30	14.00	7.9E-04	1.0E-04	8.9E-04	3.8E-04	2.7E-04	6.5E-08
i60q30	14.00	1.3E-03	1.1E-04	1.4E-03	4.7E-04	4.1E-04	1.6E-07
i240q30	14.00	9.3E-04	7.8E-05	1.0E-03	3.3E-04	2.5E-04	5.7E-08
ISOq30N	14.00	5.88	1.15	7.03	3.57	1.81	3.04
i60q30N	14.00	16.49	1.70	18.19	5.83	4.45	18.38
i240q30N	14.00	7.62	1.14	8.75	3.86	2.00	3.71
ISOagEMGpt	14.00	1.6E-04	5.5E-05	2.1E-04	1.2E-04	4.6E-05	2.0E-09
i60agEMGpt	14.00	1.4E-04	3.8E-05	1.8E-04	8.7E-05	3.7E-05	1.3E-09
i240agEMGpt	14.00	1.6E-04	3.5E-05	1.9E-04	1.1E-04	5.4E-05	2.7E-09
ISOantEMGpt	14.00	1.0E-05	6.5E-06	1.7E-05	1.2E-05	3.1E-06	9.0E-12
i60antEMGpt	14.00	1.9E-05	5.5E-06	2.5E-05	1.2E-05	4.7E-06	2.1E-11
i240antEMGpt	14.00	2.5E-05	6.0E-06	3.1E-05	1.5E-05	8.1E-06	6.1E-11
ISOEffPT	14.00	0.34	0.57	0.91	0.80	0.10	0.01
i60EffPT	14.00	0.35	0.55	0.90	0.73	0.12	0.01
i240EffPT	14.00	0.48	0.42	0.90	0.71	0.16	0.02
ISOCoact	14.00	0.23	0.05	0.27	0.12	0.07	0.00
i60Coact	14.00	0.24	0.05	0.29	0.16	0.08	0.01
i240coact	14.00	0.35	0.05	0.40	0.18	0.12	0.01

Appendix I: Descriptive Statistics – Pre-Pubertal Females

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
Tanner	35.00	0.00	1.00	1.00	1.00	0.00	0.00
Maturity	35.00	0.00	1.00	1.00	1.00	0.00	0.00
Age	35.00	4.41	8.03	12.44	9.80	1.07	1.11
YearsPHV	35.00	3.93	-3.49	0.44	-1.82	0.90	0.78
Height	35.00	30.30	124.90	155.20	139.08	8.17	64.78
Weight	35.00	34.60	20.50	55.10	35.80	8.38	68.28
PBF	35.00	28.60	7.00	35.60	21.25	8.79	75.00
BMI	35.00	13.92	12.04	25.96	18.36	3.28	10.47
LBM	35.00	20.56	17.72	38.28	27.84	5.19	26.12
ThighLeanCSA	35.00	84.48	64.38	148.86	96.33	20.23	397.48
MuscleDia	35.00	20.60	23.90	44.50	32.63	4.34	18.34
qCSA	35.00	11.06	4.49	15.55	8.51	2.29	5.11
ThighLength	35.00	10.30	27.00	37.30	32.03	2.79	7.55
ThighCirc	35.00	19.20	32.80	52.00	41.28	4.74	21.84
SFantThigh	35.00	20.50	12.20	32.70	20.29	5.85	33.20
SFpostThight	13.00	16.40	11.10	27.50	15.69	5.28	25.78
SFmedThigh	32.00	29.90	13.30	43.20	24.54	8.98	78.13
SFlatThigh	27.00	23.80	9.60	33.40	17.87	6.74	43.71
SFmeanThigh	35.00	21.75	11.90	33.65	21.21	6.73	43.96
Gsactivity	35.00	118.00	14.00	132.00	57.91	28.61	795.22
ISOPT	35.00	70.51	50.95	121.46	82.69	18.20	321.60
i60PT	35.00	54.11	40.42	94.53	63.94	15.11	221.86
i240PT	35.00	33.44	23.76	57.20	36.59	7.83	59.50
ISOPTcsa	35.00	8.68	6.40	15.08	10.01	2.04	4.05
i60PTcsa	35.00	7.03	5.34	12.36	7.72	1.63	2.57
i240PTcsa	35.00	3.91	2.43	6.34	4.45	0.88	0.76
Ptiso_60	35.00	0.43	0.02	0.45	0.22	0.10	0.01
PT60_240	35.00	0.41	0.26	0.67	0.42	0.09	0.01
Ptiso_240	35.00	0.31	0.38	0.69	0.55	0.08	0.01
ISOTtPT	35.00	2448.50	356.00	2804.50	1552.78	629.37	384790.37
i60TtPT	35.00	250.50	215.00	465.50	350.18	69.67	4715.75
i240TtPT	35.00	136.50	162.00	298.50	214.62	32.11	1001.58
ISOPrTD	35.00	441.90	209.84	651.75	393.41	116.95	13287.17
i60PrTD	35.00	356.20	188.46	544.66	342.37	98.38	9402.46
i240PrTD	35.00	337.85	144.85	482.71	286.20	72.10	5049.23
ISOPrTDcsa	35.00	51.97	23.04	75.02	47.79	13.95	188.95
i60PrTDcsa	35.00	39.60	26.21	65.81	41.11	9.71	91.62
i240PrTDcsa	35.00	34.78	17.92	52.70	34.93	8.93	77.53

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
PrTDiso60	35.00	0.85	-0.41	0.44	0.11	0.18	0.03
PrTD60240	35.00	0.74	-0.29	0.45	0.14	0.19	0.04
ISOTtPrTD	35.00	82.00	38.00	120.00	82.16	17.90	311.12
i60TtPrTD	35.00	135.00	58.00	193.00	118.84	36.00	1259.15
i240TtPrTD	35.00	94.50	41.00	135.50	68.07	18.23	322.71
ISOemd	35.00	129.00	5.00	134.00	80.97	23.98	558.39
i60emd	35.00	87.33	44.67	132.00	74.68	20.05	390.32
i240emd	35.00	56.00	39.00	95.00	63.79	15.08	220.87
ISOq30	35.00	1.1E-03	8.6E-05	1.2E-03	3.8E-04	2.5E-04	6.1E-08
i60q30	35.00	9.0E-04	1.1E-04	1.0E-03	3.3E-04	2.1E-04	4.3E-08
i240q30	35.00	1.0E-03	1.2E-04	1.1E-03	3.9E-04	2.2E-04	4.7E-08
ISOq30N	35.00	18.50	1.36	19.85	4.87	3.23	10.11
i60q30N	35.00	8.46	1.33	9.79	4.62	2.19	4.66
i240q30N	35.00	11.98	1.10	13.09	5.01	2.86	7.92
ISOagEMGpt	35.00	1.1E-04	4.6E-05	1.6E-04	9.5E-05	3.3E-05	1.0E-09
i60agEMGpt	35.00	1.2E-04	3.9E-05	1.6E-04	8.0E-05	2.8E-05	7.6E-10
i240agEMGpt	35.00	1.5E-04	4.2E-05	1.9E-04	9.6E-05	3.3E-05	1.1E-09
ISOantEMGpt	35.00	6.8E-05	6.6E-06	7.4E-05	2.1E-05	1.1E-05	1.3E-10
i60antEMGpt	35.00	6.4E-05	6.3E-06	7.0E-05	1.8E-05	1.0E-05	1.1E-10
i240antEMGpt	35.00	2.9E-05	9.6E-06	3.9E-05	2.0E-05	7.8E-06	5.8E-11
ISOEffPT	35.00	0.52	0.28	0.81	0.64	0.10	0.01
i60EffPT	35.00	0.61	0.21	0.81	0.64	0.11	0.01
i240EffPT	35.00	0.38	0.44	0.82	0.65	0.09	0.01
ISOCoact	35.00	0.46	0.11	0.56	0.22	0.09	0.01
i60Coact	35.00	0.55	0.10	0.66	0.23	0.10	0.01
i240coact	35.00	0.30	0.10	0.39	0.22	0.07	0.00

Appendix J: Descriptive Statistics – Late-Pubertal Females

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
Tanner	13.00	1.00	4.00	5.00	4.15	0.38	0.13
Maturity	13.00	0.00	2.00	2.00	2.00	0.00	0.00
Age	13.00	5.88	10.78	16.66	13.50	1.82	3.05
YearsPHV	13.00	6.39	-2.34	4.05	1.28	1.74	2.80
Height	13.00	28.60	147.80	176.40	162.00	9.04	75.40
Weight	13.00	36.80	42.90	79.70	57.90	9.52	83.70
PBF	13.00	23.60	17.40	41.00	26.02	7.88	57.26
BMI	13.00	11.20	17.37	28.58	22.07	3.19	9.42
LBM	13.00	20.89	34.30	55.20	42.53	5.80	31.00
ThighLeanCSA	13.00	51.32	113.42	164.73	129.70	16.91	264.08
MuscleDia	13.00	14.09	29.04	43.13	35.72	4.72	20.60
qCSA	13.00	7.99	6.62	14.61	10.18	2.70	6.71
ThighLength	13.00	9.00	34.00	43.00	37.27	2.49	5.75
ThighCirc	13.00	11.40	43.90	55.30	49.67	3.43	10.89
SFantThigh	13.00	32.50	14.40	46.90	26.24	10.11	94.39
SFpostThight	1.00	0.00	26.00	26.00	26.00	#DIV/0!	0.00
SFmedThigh	13.00	25.60	22.60	48.20	35.02	9.67	86.25
SFlatThigh	4.00	21.40	19.00	40.40	27.93	8.99	60.61
SFmeanThigh	13.00	25.78	19.25	45.03	29.84	8.66	69.26
Gsactivity	13.00	71.00	5.00	76.00	41.77	20.39	383.72
ISOPT	13.00	130.35	84.15	214.50	155.12	35.86	1186.72
i60PT	13.00	97.42	75.00	172.42	114.15	27.86	716.26
i240PT	13.00	51.84	31.67	83.51	61.90	15.57	223.90
ISOPTcsa	13.00	22.57	5.76	28.33	16.30	5.39	26.84
i60PTcsa	13.00	9.92	5.65	15.57	11.71	3.00	8.33
i240PTcsa	13.00	6.73	2.62	9.36	6.41	1.99	3.66
Ptiso_60	13.00	0.43	0.02	0.45	0.26	0.12	0.01
PT60_240	13.00	0.42	0.28	0.70	0.45	0.11	0.01
Ptiso_240	13.00	0.35	0.45	0.80	0.59	0.10	0.01
ISOTtPT	13.00	1885.33	685.67	2571.00	1681.32	511.82	241810.64
i60TtPT	13.00	320.67	261.33	582.00	375.53	97.48	8770.99
i240TtPT	13.00	111.00	157.00	268.00	217.00	25.66	607.91
ISOPrTD	13.00	430.74	529.73	960.47	743.52	132.70	16254.38
i60PrTD	13.00	709.73	334.40	1044.14	642.28	206.84	39491.80
i240PrTD	13.00	320.02	233.64	553.66	410.08	101.35	9481.60
ISOPrTDcsa	13.00	71.98	36.26	108.23	76.92	19.19	339.77
i60PrTDcsa	13.00	64.77	27.58	92.36	65.03	19.04	334.65
i240PrTDcsa	13.00	45.34	17.25	62.59	42.33	12.97	155.16

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
PrTDiso60	13.00	0.63	-0.20	0.43	0.15	0.17	0.03
PrTD60240	13.00	0.31	0.21	0.52	0.34	0.10	0.01
ISOTtPrTD	13.00	84.50	67.50	152.00	87.18	22.20	455.00
i60TtPrTD	13.00	96.50	85.50	182.00	112.53	25.49	599.98
i240TtPrTD	13.00	102.00	55.00	157.00	73.10	26.11	629.40
ISOemd	13.00	50.33	36.67	87.00	61.82	16.36	247.03
i60emd	13.00	76.00	34.00	110.00	62.35	18.96	331.86
i240emd	13.00	59.00	18.00	77.00	50.45	14.74	200.47
ISOq30	13.00	6.6E-04	2.0E-04	8.6E-04	4.1E-04	1.9E-04	3.4E-08
i60q30	13.00	6.6E-04	1.7E-04	8.2E-04	3.9E-04	2.3E-04	4.7E-08
i240q30	13.00	4.3E-04	2.7E-04	7.0E-04	4.2E-04	1.3E-04	1.5E-08
ISOq30N	13.00	8.62	3.42	12.04	5.29	2.31	4.93
i60q30N	13.00	8.25	3.39	11.64	6.68	2.94	7.97
i240q30N	13.00	16.05	2.76	18.81	7.56	4.34	17.39
ISOagEMGpt	13.00	9.3E-05	6.7E-05	1.6E-04	1.0E-04	3.0E-05	8.2E-10
i60agEMGpt	13.00	7.7E-05	2.7E-05	1.0E-04	6.5E-05	2.0E-05	3.6E-10
i240agEMGpt	13.00	1.2E-04	3.8E-05	1.6E-04	7.5E-05	3.3E-05	1.0E-09
ISOantEMGpt	13.00	1.3E-05	1.1E-05	2.4E-05	1.6E-05	4.8E-06	2.2E-11
i60antEMGpt	13.00	2.8E-05	7.1E-06	3.5E-05	1.4E-05	7.5E-06	5.2E-11
i240antEMGpt	13.00	1.9E-05	4.2E-06	2.4E-05	1.4E-05	6.0E-06	3.3E-11
ISOEffPT	13.00	0.32	0.54	0.86	0.71	0.09	0.01
i60EffPT	13.00	0.61	0.20	0.81	0.63	0.17	0.03
i240EffPT	13.00	0.42	0.42	0.84	0.67	0.14	0.02
ISOCoact	13.00	0.22	0.07	0.30	0.17	0.06	0.00
i60Coact	13.00	0.72	0.11	0.82	0.25	0.19	0.03
i240coact	13.00	0.32	0.08	0.41	0.21	0.10	0.01

Appendix K: Descriptive Statistics – Adult Females

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
Tanner	15.00	0.00	6.00	6.00	6.00	0.00	0.00
Maturity	15.00	0.00	3.00	3.00	3.00	0.00	0.00
Age	15.00	8.21	19.30	27.50	21.42	2.08	4.04
YearsPHV	0	0	0	0	0	0	0
Height	15.00	23.10	159.30	182.40	166.68	6.91	44.54
Weight	15.00	27.80	52.00	79.80	62.97	7.27	49.28
PBF	15.00	18.50	18.80	37.30	24.44	4.81	21.55
BMI	15.00	7.20	19.40	26.60	22.65	2.13	4.22
LBM	15.00	17.57	41.05	58.62	48.44	4.28	17.08
ThighLeanCSA	15.00	61.54	134.09	195.63	161.72	19.82	366.72
MuscleDia	15.00	20.85	31.45	52.30	40.65	5.54	28.63
qCSA	15.00	13.71	7.77	21.48	13.20	3.72	12.91
ThighLength	15.00	8.30	34.00	42.30	37.31	2.22	4.62
ThighCirc	15.00	12.00	46.70	58.70	52.22	3.27	9.96
SFantThigh	15.00	29.00	13.80	42.80	23.09	7.27	49.33
SFpostThight	1.00	0.00	12.80	12.80	12.80	#DIV/0!	0.00
SFmedThigh	13.00	18.20	15.80	34.00	23.31	5.64	29.38
SFlatThigh	9.00	15.80	11.00	26.80	19.46	5.35	25.43
SFmeanThigh	15.00	28.60	14.20	42.80	22.97	7.01	45.90
Gsactivity	15.00	86.00	26.00	112.00	67.33	28.40	752.76
ISOPT	15.00	132.61	126.01	258.63	183.43	35.40	1169.76
i60PT	15.00	68.85	81.40	150.26	126.59	17.64	290.45
i240PT	15.00	60.75	24.62	85.37	56.36	17.25	277.57
ISOPTcsa	15.00	15.38	8.51	23.89	14.77	4.63	20.04
i60PTcsa	15.00	13.93	5.40	19.33	10.31	3.50	11.46
i240PTcsa	15.00	6.50	2.04	8.54	4.56	1.96	3.60
Ptiso_60	15.00	0.46	0.06	0.51	0.29	0.14	0.02
PT60_240	15.00	0.39	0.41	0.79	0.56	0.11	0.01
Ptiso_240	15.00	0.36	0.50	0.86	0.69	0.11	0.01
ISOTtPT	15.00	1948.00	663.00	2611.00	1532.63	489.24	223396.63
i60TtPT	15.00	323.00	270.00	593.00	398.82	84.67	6691.65
i240TtPT	15.00	151.00	132.00	283.00	224.84	42.39	1676.94
ISOPrTD	15.00	760.37	373.34	1133.70	772.73	206.18	39675.70
i60PrTD	15.00	657.31	301.04	958.35	661.92	169.27	26743.72
i240PrTD	15.00	340.25	208.17	548.42	360.48	97.33	8842.49
ISOPrTDcsa	15.00	83.88	29.66	113.54	63.02	25.10	587.86
i60PrTDcsa	15.00	67.98	26.35	94.34	53.74	20.71	400.29
i240PrTDcsa	15.00	36.69	12.64	49.33	29.27	11.27	118.57

Variable	N	Range	Minimum	Maximum	Mean	SD	Variance
PrTDiso60	15.00	1.10	-0.69	0.40	0.11	0.26	0.06
PrTD60240	15.00	0.36	0.28	0.64	0.44	0.12	0.01
ISOTtPrTD	15.00	256.50	66.50	323.00	113.52	66.99	4188.62
i60TtPrTD	15.00	159.50	93.00	252.50	135.50	40.87	1559.21
i240TtPrTD	15.00	152.67	55.33	208.00	94.02	44.29	1830.79
ISOemd	15.00	66.00	19.00	85.00	61.40	16.74	261.51
i60emd	15.00	54.00	35.00	89.00	62.03	15.41	221.59
i240emd	15.00	66.00	28.00	94.00	58.62	16.94	267.86
ISOq30	15.00	5.4E-04	1.5E-04	6.9E-04	3.5E-04	1.3E-04	1.6E-08
i60q30	15.00	1.2E-03	1.3E-04	1.3E-03	3.3E-04	2.7E-04	7.0E-08
i240q30	15.00	4.5E-04	1.3E-04	5.8E-04	2.8E-04	1.5E-04	2.1E-08
ISOq30N	15.00	6.66	1.65	8.30	4.25	1.79	3.00
i60q30N	15.00	11.27	2.18	13.45	5.38	2.80	7.33
i240q30N	15.00	9.25	2.09	11.34	5.60	2.86	7.66
ISOagEMGpt	15.00	1.7E-04	6.0E-05	2.3E-04	1.0E-04	4.1E-05	1.6E-09
i60agEMGpt	15.00	1.2E-04	3.3E-05	1.5E-04	7.0E-05	3.7E-05	1.3E-09
i240agEMGpt	15.00	1.6E-04	2.7E-05	1.9E-04	7.3E-05	4.4E-05	1.8E-09
ISOantEMGpt	15.00	2.7E-05	5.3E-06	3.2E-05	1.1E-05	6.7E-06	4.2E-11
i60antEMGpt	15.00	1.9E-05	4.9E-06	2.4E-05	9.9E-06	5.5E-06	2.8E-11
i240antEMGpt	15.00	6.4E-05	3.6E-06	6.8E-05	1.3E-05	1.6E-05	2.3E-10
ISOEffPT	15.00	0.41	0.52	0.93	0.79	0.12	0.01
i60EffPT	15.00	0.74	0.18	0.92	0.71	0.19	0.03
i240EffPT	15.00	0.84	0.07	0.91	0.68	0.21	0.04
ISOCoact	15.00	0.28	0.04	0.32	0.12	0.08	0.01
i60Coact	15.00	0.66	0.04	0.70	0.19	0.17	0.03
i240coact	15.00	0.82	0.05	0.87	0.21	0.20	0.04

Appendix L – Leg Extension Characteristics

		PPm	LPm	Am	PPf	LPf	Af	Effect
PT	Isometric	82.85 ± 29.43^{a,b}	187.32 ± 77.74^{a}	309.34 ± 65.93^{c}	82.69 ± 18.20^{a,b}	155.12 ± 35.86^{a}	183.43 ± 35.40^{c}	S, M, V,
(Absolute)	60°/s	60.11 ± 18.12^{a,b}	124.36 ± 50.78^{a}	210.05 ± 30.01^{c}	63.94 ± 15.11^{a,b}	114.16 ± 27.86	126.59 ± 17.64^{c}	S*M,S*V,M*V
	240°/s	35.78 ± 10.42^{a,b}	70.10 ± 31.91^{a}	109.08 ± 35.65^{c}	36.59 ± 7.83	61.90 ± 15.57	56.36 ± 17.25^{c}	S*M*V
PT	Isometric	12.19 ± 3.9^{a,b,c}	19.40 ± 4.56	18.94 ± 4.68^{c}	10.02 ± 2.04^{a,b,c}	16.30 ± 5.39	14.77 ± 4.63^{c}	
(PerCSA)	60°/s	8.88 ± 2.45^{a,b,c}	12.88 ± 3.24	13.02 ± 3.50^{c}	7.72 ± 1.63^{a,b,c}	11.71 ± 3.00	10.31 ± 3.50^{c}	S,M,V, S*V, M*V
	240°/s	5.30 ± 1.50^{b,c}	7.26 ± 2.28	6.78 ± 2.71^{c}	4.45 ± 0.88^{a,b,c}	6.41 ± 1.99^{b}	4.56 ± 1.97^{c}	
PrTD	Isometric	406.02 ± 140.31^{a,b}	873.18 ± 441.40^{a}	1405.11 ± 380.85^{c}	393.41 ± 116.95^{a,b}	743.52 ± 132.70	772.73 ± 206.17^{c}	S, M, V,
(Absolute)	60°/s	338.09 ± 127.47^{a,b}	732.44 ± 364.56^{a}	1303.22 ± 315.01^{c}	342.37 ± 98.38^{a,b}	642.28 ± 206.84	661.92 ± 169.28^{c}	S*M,S*V,M*V
	240°/s	268.13 ± 63.69^{a,b}	472.67 ± 231.73^{a}	751.08 ± 293.94^{c}	286.20 ± 72.10	410.09 ± 101.35	360.49 ± 97.34^{c}	S*M*V
PrTD	Isometric	60.12 ± 19.92^{a,b,c}	89.57 ± 32.73	87.36 ± 29.51^{c}	47.79 ± 13.9^{a,b,c}	76.92 ± 19.19	63.02 ± 25.10^{c}	
(PerCSA)	60°/s	49.96 ± 17.91^{a,b,c}	75.85 ± 28.57	80.39 ± 24.44^{c}	41.11 ± 9.71^{a,b,c}	65.03 ± 19.04	53.74 ± 20.71^{c}	S,M,V, S*V, M*V
	240°/s	40.44 ± 12.19	48.89 ± 16.07	46.12 ± 19.10^{c}	34.93 ± 8.93	42.34 ± 12.97^{a}	29.27 ± 11.27^{c}	
Q30	Isometric	4.0E-04 ± 2.5E-04	5.5E-04 ± 4.0E-04	3.8E-04 ± 2.7E-04	3.8E-04 ± 2.5E-04	4.1E-04 ± 1.9E-04	3.5E-04 ± 1.3E-04	
(Absolute)	60°/s	3.8E-04 ± 3.0E-04	4.7E-04 ± 3.3E-04	4.7E-04 ± 4.1E-04	3.3E-04 ± 2.1E-04	3.9E-04 ± 2.3E-04	3.3E-04 ± 2.7E-04	
	240°/s	3.1E-04 ± 1.4E-04	5.1E-04 ± 4.5E-04	3.3E-04 ± 2.5E-04	3.9E-04 ± 2.2E-04	4.2E-04 ± 1.3E-04	2.8E-04 ± 1.5E-04	
Q30	Isometric	4.98 ± 2.54	5.36 ± 2.84	3.57 ± 1.81	4.87 ± 3.23	5.29 ± 2.31	4.25 ± 1.79	M, M*V
(PerEMGamp)	60°/s	5.28 ± 3.52	5.67 ± 2.58	5.83 ± 4.44	4.62 ± 2.19^{b}	6.68 ± 2.94	5.38 ± 2.80	
	240°/s	4.19 ± 2.36	5.03 ± 2.88	3.86 ± 2.00	5.01 ± 2.86^{a}	7.56 ± 4.34	5.6 ± 2.87	
EMD	Isometric	72.7 ± 19.0	66.8 ± 11.5	62.4 ± 21.7	81.0 ± 24.0^{a,b}	61.8 ± 16.4	61.4 ± 16.7	
(s)	60°/s	76.5 ± 29.1	63.8 ± 18.1	63.0 ± 23.8	74.7 ± 20.0	62.3 ± 19.0	62.0 ± 15.4	M, V
	240°/s	65.7 ± 13.8	54.6 ± 17.0	53.3 ± 19.2	63.8 ± 15.1^{a}	50.5 ± 14.7	58.6 ± 16.9	
AgonistEMG	Isometric	0.1 ± 0.04	0.13 ± 0.05	0.12 ± 0.05	0.09 ± 0.03	0.1 ± 0.03	0.1 ± 0.04	
(mV)	60°/s	0.08 ± 0.03	0.09 ± 0.04^{c}	0.09 ± 0.04	0.08 ± 0.03	0.07 ± 0.02^{c}	0.07 ± 0.04	S, V, M*V
	240°/s	0.09 ± 0.04	0.12 ± 0.06^{c}	0.11 ± 0.05	0.1 ± 0.03	0.07 ± 0.03^{c}	0.07 ± 0.04	
AntagonistEMG	Isometric	0.016 ± 0.005	0.018 ± 0.008^{a}	0.012 ± 0.003	0.021 ± 0.012^{a}	0.02 ± 0.005	0.01 ± 0.006	
	60°/s	0.015 ± 0.005	0.014 ± 0.007	0.012 ± 0.005	0.018 ± 0.011^{a}	0.01 ± 0.008	0.01 ± 0.006	M, V
	240°/s	0.016 ± 0.005	0.017 ± 0.009	0.015 ± 0.008	0.02 ± 0.008	0.01 ± 0.006	0.01 ± 0.016	
Efficiency	Isometric	0.7 ± 0.11	0.74 ± 0.12	0.8 ± 0.10	0.64 ± 0.11^{a}	0.71 ± 0.09	0.79 ± 0.12	
	60°/s	0.67 ± 0.13	0.73 ± 0.12	0.73 ± 0.12	0.64 ± 0.11	0.63 ± 0.17	0.71 ± 0.19	M, V, M*V
	240°/s	0.68 ± 0.11	0.74 ± 0.13	0.71 ± 0.16	0.65 ± 0.09	0.67 ± 0.14	0.68 ± 0.21	
Cocontraction	Isometric	0.18 ± 0.09	0.16 ± 0.09	0.12 ± 0.07	0.22 ± 0.09^{a}	0.19 ± 0.06	0.12 ± 0.08	
	60°/s	0.21 ± 0.10	0.16 ± 0.10	0.16 ± 0.08	0.23 ± 0.10	0.25 ± 0.19	0.19 ± 0.17	V, M*V
	240°/s	0.19 ± 0.08	0.16 ± 0.10	0.18 ± 0.12	0.22 ± 0.07	0.21 ± 0.11	0.21 ± 0.20	
Attain240°/s	240°/s	4.76%^{a,b}	52.94%	78.57%	2.86%^{a,b}	64.29%	46.67%	

Table 1: Values are presented as M ± SD. [a] = significantly different than sex matched adult group, [b] = significantly different than sex-matched late-pubertal group, and [c] = significantly different than maturity matched-matched female group.

Appendix M – Summary of ANOVA’s

	Main Effect			Interaction			
	Sex	Maturity	Velocity	Sex*Maturity	Sex*Velocity	Maturity*Velocity	Sex*Maturity*Velocity
PT	<.001	<.001	<.001	<.001	<.001	<.001	<.001
PTcsa	<.001	<.001	<.001	-	<.001	<.001	-
PrTD	<.001	<.001	<.001	<.001	<.001	<.001	<.01
PrTDcsa	<.001	<.001	<.001	-	<.05	<.001	-
EMD	-	<.001	<.001	-	-	-	-
Q30	N/A	N/A	-	N/A	-	-	-
Q30N	-	<.05	-	-	<.05	-	-
AgEMG	N/A	N/A	<.001	N/A	-	<.01	-
AntEMG	N/A	N/A	<.01	N/A	-	-	-
Efficiency	-	<.05	<.001	-	-	<.01	-
Coactivation	-	-	<.001	-	-	<.05	-

Appendix N –Bivariate Correlations: Isometric Contractions

		qCSA	ISOPT	ISOPTcsa	ISOPrTD	ISOPrTDcsa	ISOagEMGpt	ISOEffPT	ISOCocon	ISOq30	ISOq30N	ISOemd
qCSA	r	1	.758**	.069	.675**	.000	.079	.268**	-.253**	-.074	-.147	-.111
	p		.000	.465	.000	.997	.399	.004	.006	.432	.118	.238
ISOPT	r	.758**	1	.663**	.931**	.540**	.246**	.372**	-.347**	.039	-.158	-.286**
	p	.000		.000	.000	.000	.008	.000	.000	.677	.092	.002
ISOPTcsa	r	.069	.663**	1	.636**	.861**	.309**	.286**	-.264**	.139	-.087	-.306**
	p	.465	.000		.000	.000	.001	.002	.004	.139	.357	.001
ISOPrTD	r	.675**	.931**	.636**	1	.692**	.254**	.384**	-.356**	.095	-.097	-.306**
	p	.000	.000	.000		.000	.006	.000	.000	.312	.304	.001
ISOPrTDcsa	r	.000	.540**	.861**	.692**	1	.279**	.249**	-.224*	.209*	.015	-.311**
	p	.997	.000	.000	.000		.003	.007	.016	.025	.872	.001
ISOagEMGpt	r	.079	.246**	.309**	.254**	.279**	1	.521**	-.482**	.482**	-.147	-.037
	p	.399	.008	.001	.006	.003		.000	.000	.000	.117	.697
ISOEffPT	r	.268**	.372**	.286**	.384**	.249**	.521**	1	-.993**	.209*	-.143	-.113
	p	.004	.000	.002	.000	.007	.000		.000	.025	.126	.231
ISOCocon	r	-.253**	-.347**	-.264**	-.356**	-.224*	-.482**	-.993**	1	-.184*	.147	.105
	p	.006	.000	.004	.000	.016	.000	.000		.049	.117	.262
ISOq30	r	-.074	.039	.139	.095	.209*	.482**	.209*	-.184*	1	.704**	-.302**
	p	.432	.677	.139	.312	.025	.000	.025	.049		.000	.001
ISOq30N	r	-.147	-.158	-.087	-.097	.015	-.147	-.143	.147	.704**	1	-.424**
	p	.118	.092	.357	.304	.872	.117	.126	.117	.000		.000
ISOemd	r	-.111	-.286**	-.306**	-.306**	-.311**	-.037	-.113	.105	-.302**	-.424**	1
	p	.238	.002	.001	.001	.001	.697	.231	.262	.001	.000	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

r . Pearson Correlation, *p*. Significance

Appendix O –Bivariate Correlations: 60°/s Contractions

		qCSA	i60PT	i60PTcsa	i60PrTD	i60PrTDcsa	i60agEMGpt	i60EffPT	i60Cocon	i60q30	i60q30N	i60emd
qCSA	r	1	.759**	.008	.707**	.082	-.054	.075	-.053	.015	.039	-.091
	p		.000	.935	.000	.385	.563	.428	.574	.871	.678	.335
i60PT	r	.759**	1	.624**	.963**	.646**	.098	.180	-.132	.182	.125	-.211*
	p	.000		.000	.000	.000	.300	.054	.161	.051	.182	.024
i60PTcsa	r	.008	.624**	1	.609**	.920**	.176	.174	-.129	.210*	.119	-.252**
	p	.935	.000		.000	.000	.061	.063	.171	.024	.207	.007
i60PrTD	r	.707**	.963**	.609**	1	.724**	.091	.142	-.099	.234*	.171	-.219*
	p	.000	.000	.000		.000	.336	.129	.292	.012	.068	.019
i60PrTDcsa	r	.082	.646**	.920**	.724**	1	.160	.125	-.085	.279**	.188*	-.261**
	p	.385	.000	.000	.000		.089	.183	.369	.003	.044	.005
i60agEMGpt	r	-.054	.098	.176	.091	.160	1	.477**	-.425**	.386**	-.130	.109
	p	.563	.300	.061	.336	.089		.000	.000	.000	.167	.248
i60EffPT	r	.075	.180	.174	.142	.125	.477**	1	-.976**	.217*	-.049	-.018
	p	.428	.054	.063	.129	.183	.000		.000	.020	.601	.850
i60Cocon	r	-.053	-.132	-.129	-.099	-.085	-.425**	-.976**	1	-.201*	.038	.031
	p	.574	.161	.171	.292	.369	.000	.000		.031	.689	.744
i60q30	r	.015	.182	.210*	.234*	.279**	.386**	.217*	-.201*	1	.811**	-.481**
	p	.871	.051	.024	.012	.003	.000	.020	.031		.000	.000
i60q30N	r	.039	.125	.119	.171	.188*	-.130	-.049	.038	.811**	1	-.572**
	p	.678	.182	.207	.068	.044	.167	.601	.689	.000		.000
i60emd	r	-.091	-.211*	-.252**	-.219*	-.261**	.109	-.018	.031	-.481**	-.572**	1
	p	.335	.024	.007	.019	.005	.248	.850	.744	.000	.000	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

r . Pearson Correlation, *p*. Significance

Appendix P –Bivariate Correlations: 240°/s Contractions

		qCSA	i240PT	i240PTcsa	i240PrTD	i240PrTDcsa	i240agEMGpt	i240EffPT	i240cocon	i240q30	i240q30N	i240emd
qCSA	r	1	.658**	-.120	.633**	-.220*	-.068	.010	.011	-.068	-.009	-.091
	p		.000	.203	.000	.018	.471	.917	.904	.469	.926	.333
i240PT	r	.658**	1	.626**	.961**	.504**	.282**	.182	-.141	.191*	-.103	-.232*
	p	.000		.000	.000	.000	.002	.052	.134	.040	.272	.013
i240PTcsa	r	-.120	.626**	1	.575**	.906**	.406**	.206*	-.174	.301**	-.121	-.267**
	p	.203	.000		.000	.000	.000	.027	.064	.001	.198	.004
i240PrTD	r	.633**	.961**	.575**	1	.564**	.291**	.166	-.134	.244**	-.065	-.248**
	p	.000	.000	.000		.000	.002	.077	.154	.009	.489	.008
i240PrTDcsa	r	-.220*	.504**	.906**	.564**	1	.423**	.176	-.158	.400**	-.044	-.295**
	p	.018	.000	.000	.000		.000	.060	.092	.000	.639	.001
i240agEMGpt	r	-.068	.282**	.406**	.291**	.423**	1	.490**	-.434**	.406**	-.419**	-.010
	p	.471	.002	.000	.002	.000		.000	.000	.000	.000	.913
i240EffPT	r	.010	.182	.206*	.166	.176	.490**	1	-.982**	.131	-.211*	-.062
	p	.917	.052	.027	.077	.060	.000		.000	.163	.023	.509
i240cocon	r	.011	-.141	-.174	-.134	-.158	-.434**	-.982**	1	-.128	.176	.059
	p	.904	.134	.064	.154	.092	.000	.000		.174	.060	.531
i240q30	r	-.068	.191*	.301**	.244**	.400**	.406**	.131	-.128	1	.525**	-.400**
	p	.469	.040	.001	.009	.000	.000	.163	.174		.000	.000
i240q30N	r	-.009	-.103	-.121	-.065	-.044	-.419**	-.211*	.176	.525**	1	-.430**
	p	.926	.272	.198	.489	.639	.000	.023	.060	.000		.000
i240emd	r	-.091	-.232*	-.267**	-.248**	-.295**	-.010	-.062	.059	-.400**	-.430**	1
	p	.333	.013	.004	.008	.001	.913	.509	.531	.000	.000	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

r . Pearson Correlation, *p*. Significance